Lecture 11

Time-domain EM with inductive sources

GEOL 4397: Electromagnetic Methods for Exploration
GEOL 6398: Special Problems

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Oct. 4th, 2018

UNIVERSITY of HOUSTON
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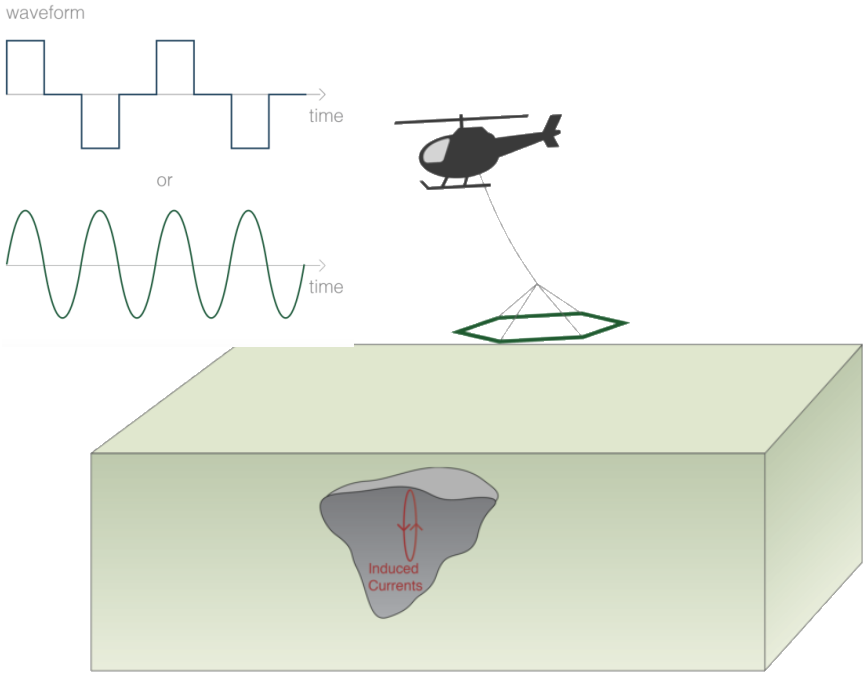
EARTH AND ATMOSPHERIC SCIENCES

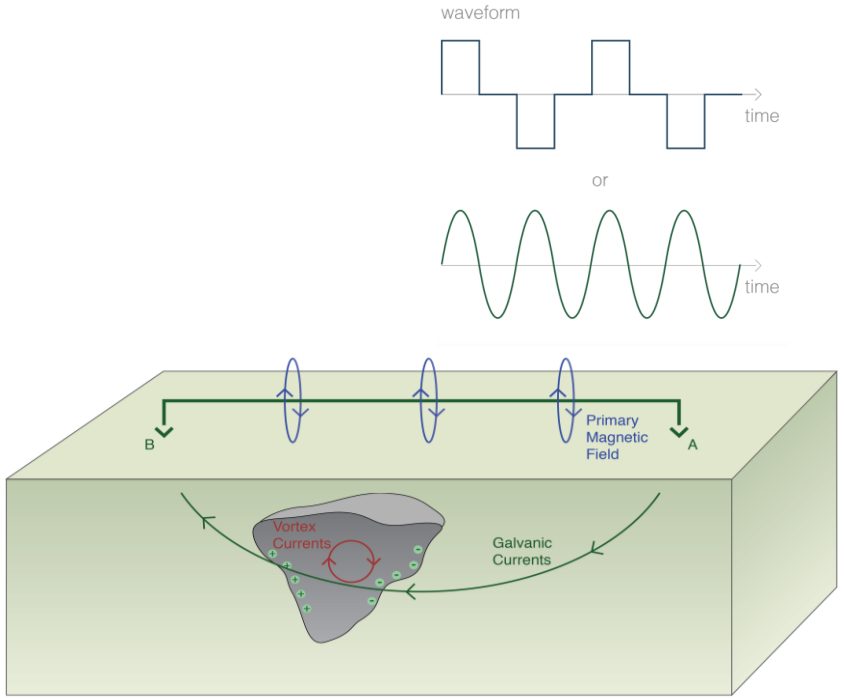
Outline

- EM sources
- Airborne EM in a homogeneous halfspace
- Airborne EM in a layered Earth model
- Airborne TEM systems
- Case history: Kasted
- Horizontal magnetic dipole (optional)

Inductive source vs Grounded sources



Inductive sources



Grounded sources

No direct contact between transmitter and the Earth's subsurface

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Dipole sources

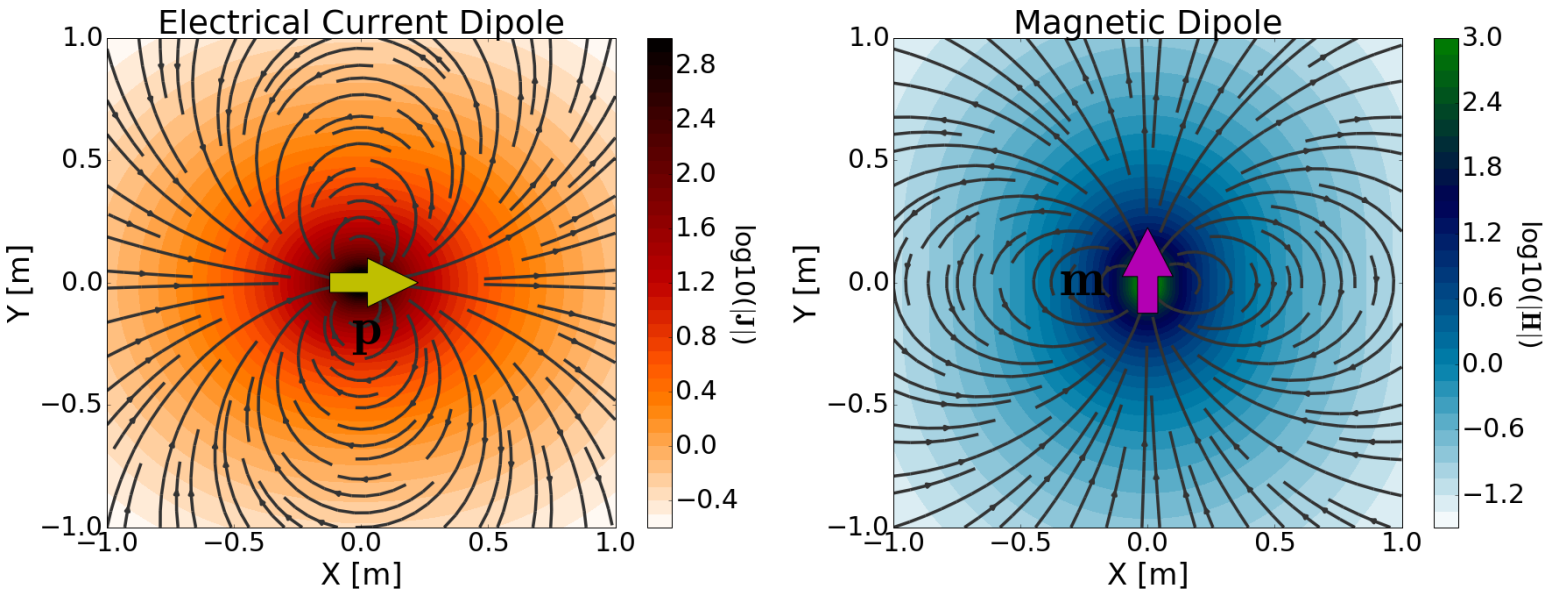
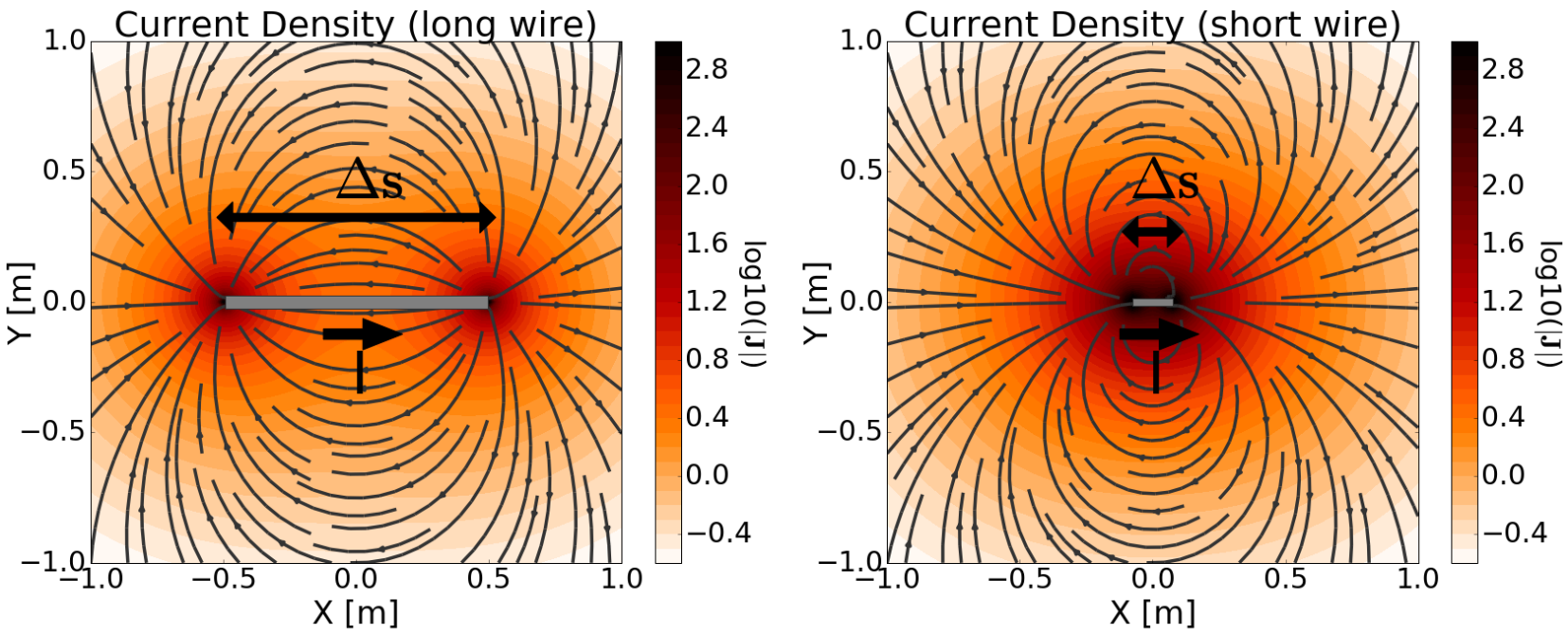


Fig. 65 (Left) Electrical current dipole ($\mathbf{p}$) oriented in the $\hat{x}$ direction and the primary current density ($\mathbf{J}$) it produces. (Right) Magnetic dipole ($\mathbf{m}$) oriented in the $\hat{y}$ direction and the primary magnetic field ($\mathbf{H}$) it produces.

https://em.geosci.xyz/content/maxwell1_fundamentals/dipole_sources_in_homogeneous_media/index.html

Wire model for an electrical current dipole

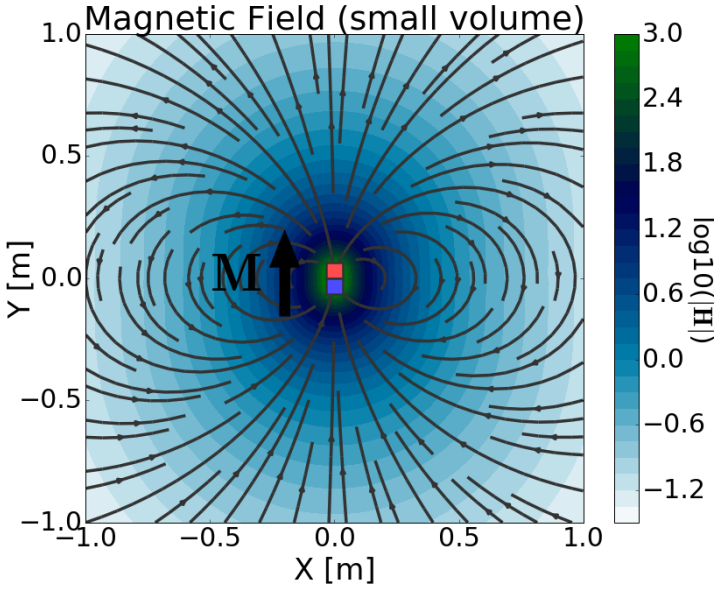


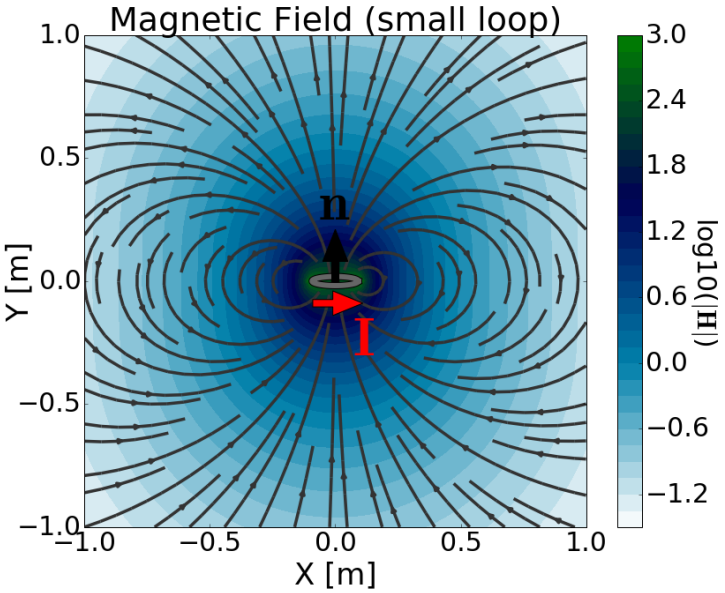
The electrical current dipole can be thought of as an infinitesimally short length of wire which carries a current, i.e. when Δs becomes small.

https://em.geosci.xyz/content/maxwell1_fundamentals/dipole_sources_in_homogeneous_media/electric_dipole_definition/index.html

Magnetic dipole

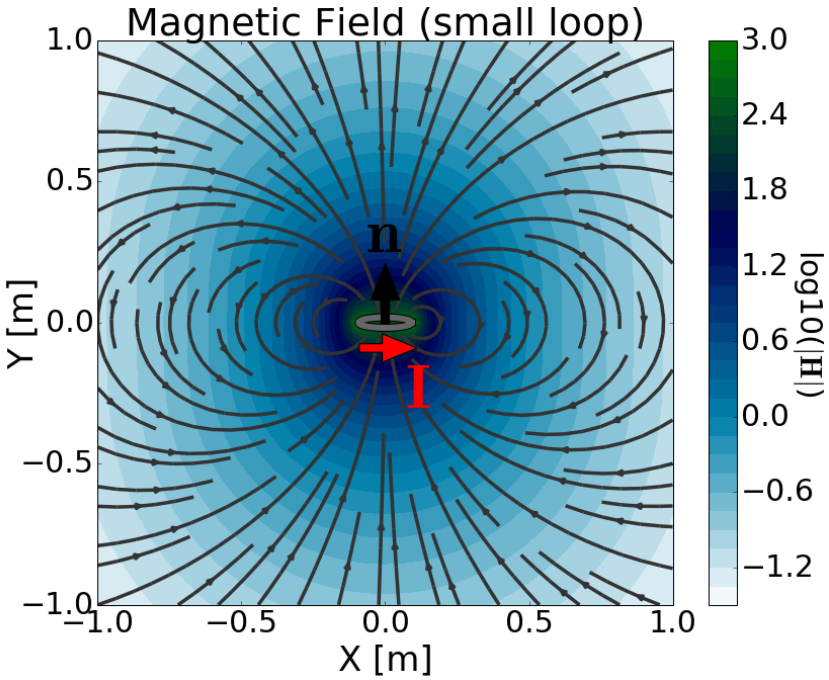
- Two models: magnetized volume model and current loop model
- The first model describes the magnetic dipole as an infinitesimally small volume of magnetized materials (i.e., a very small bar magnet)
- The second model describes the magnetic dipole using an infinitesimally small current loop

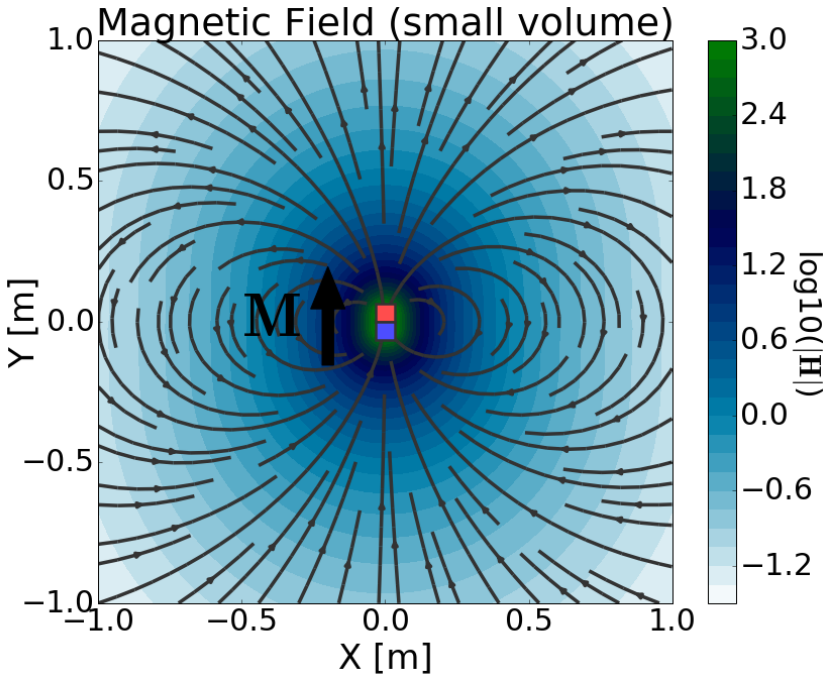




https://em.geosci.xyz/content/maxwell1_fundamentals/dipole_sources_in_homogeneous_media/magnetic_dipole_definition/index.html

Vertical magnetic dipole (VMD)





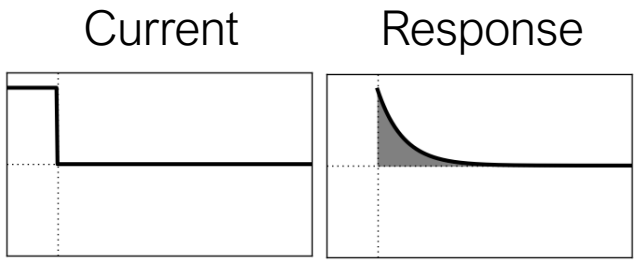
A horizontal current loop is called a vertical magnetic dipole because the magnetic field from it is similar to that from a vertical bar magnet

Reading materials on dipole sources (optional)

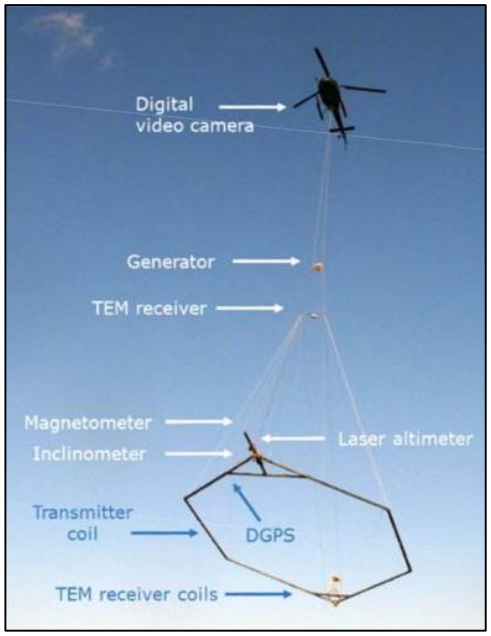
- https://em.geosci.xyz/content/maxwell1_fundamentals/dipole_sources_in_homogeneous_media/index.html

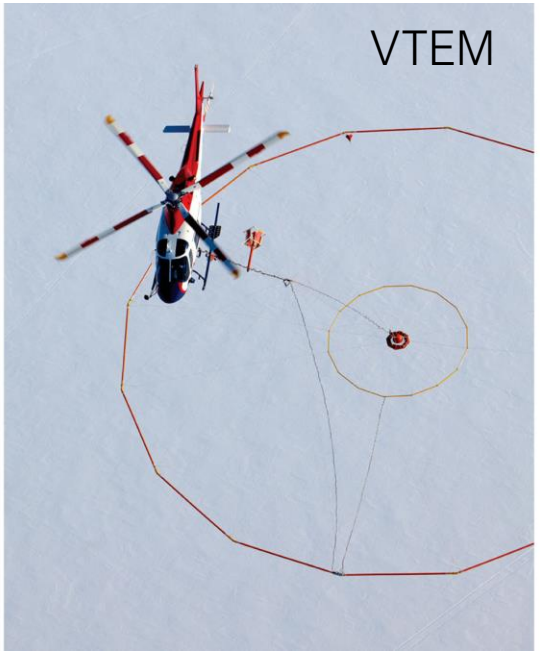
Receiver: Time Domain

- Primary field has off-time
- Measure secondary fields
- Receivers can be mounted on transmitter loop or above it

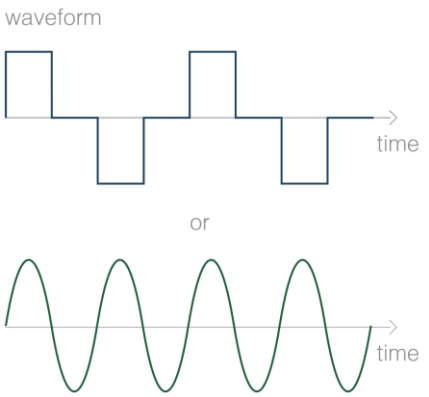


SkyTEM

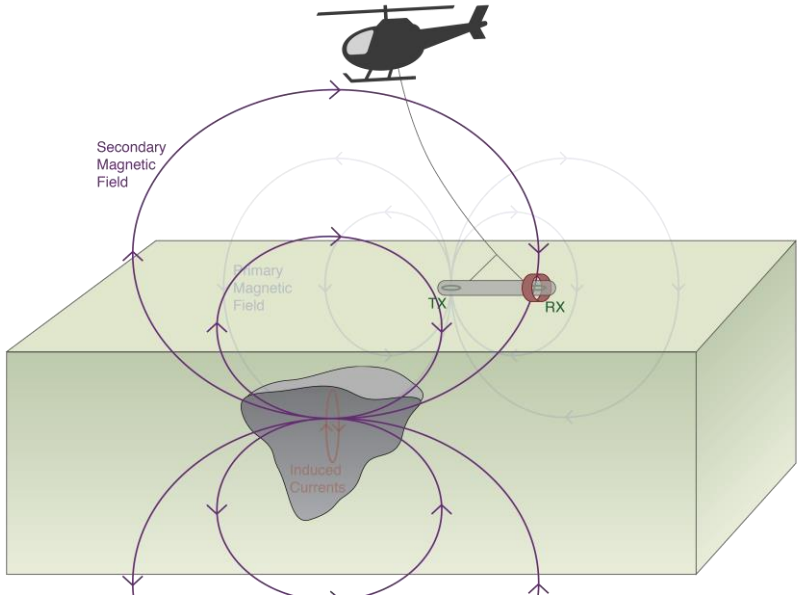




Basic Experiment



- **Transmitter:**
  - Produces a primary magnetic field
- **Exciting the target:**
  - Time varying magnetic fields generate electric fields everywhere
  - Producing currents in conductors
- **Receiver:**
  - Induced currents produce secondary magnetic fields



Reading materials on airborne EM systems (optional)

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ARTICLE

Airborne Electromagnetic Systems – State of the Art and Future Directions

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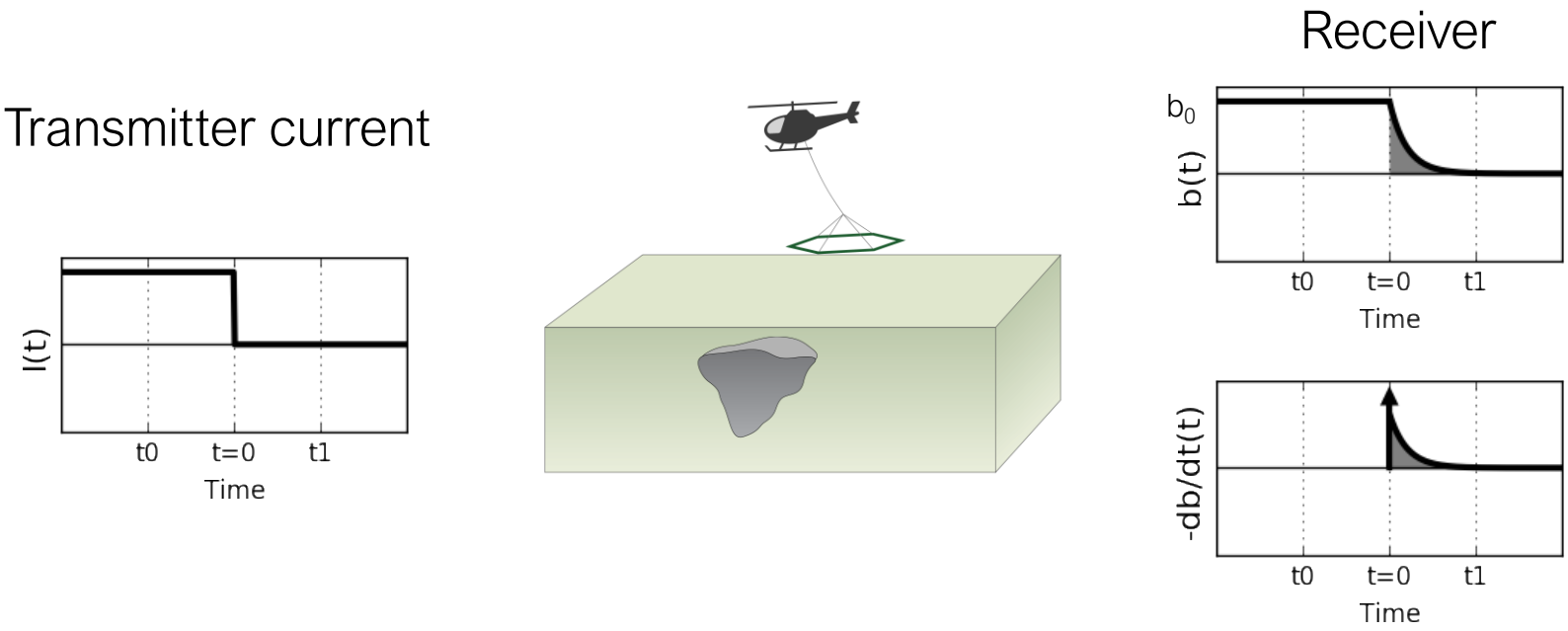
Airborne electromagnetics (AEM) is easily one of the most popular geophysical methods used in mineral exploration around the world and is possibly second to only aeromagnetics-radiometrics as being the most widely deployed. AEM was initially

https://csegrecorder.com/articles/view/airborne-electromagnetic-systems-state-of-the-art-and-future-directions

Time domain EM with Inductive Sources



- At t = t0, b is constant, no EM signal
- At t = 0: Current interrupted, begin to induce current in the Earth
- At t = t1: No primary field, only secondary field

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Vertical Magnetic Dipole over a halfspace

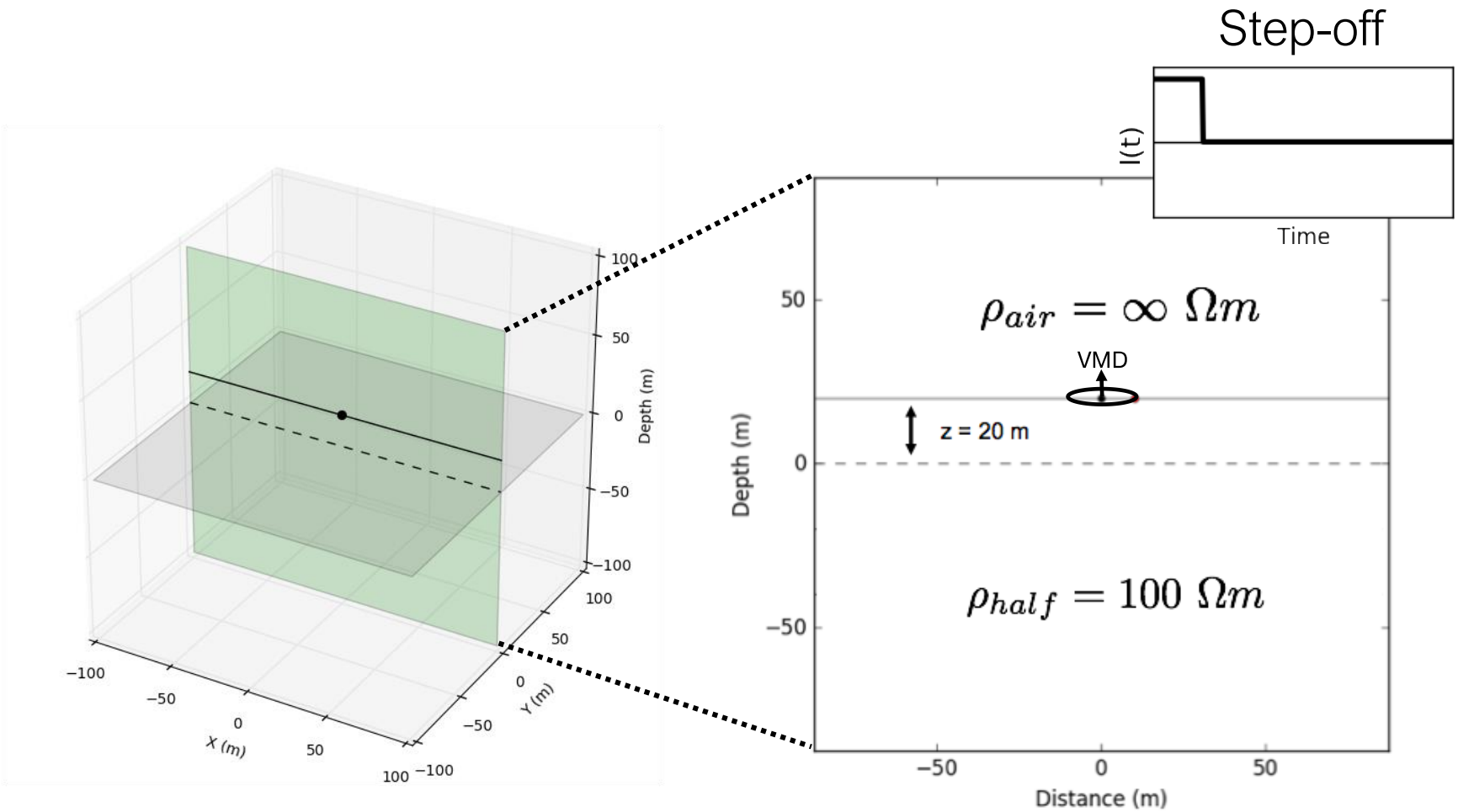


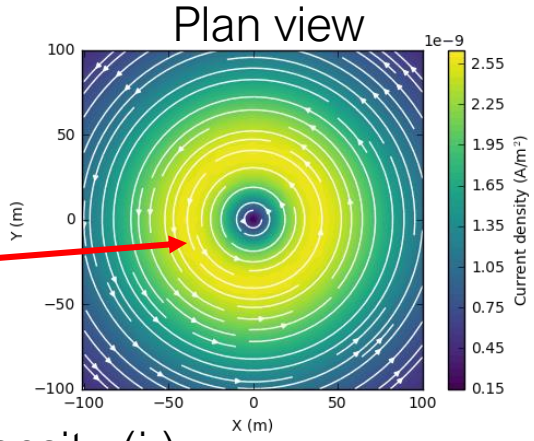
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

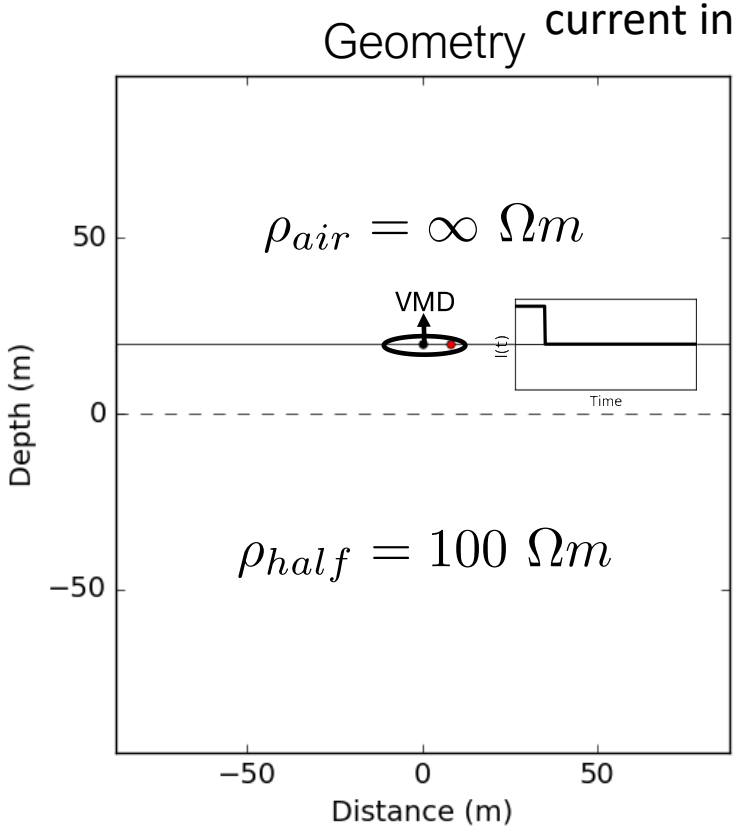
What would happen if I turn off the current in the loop?

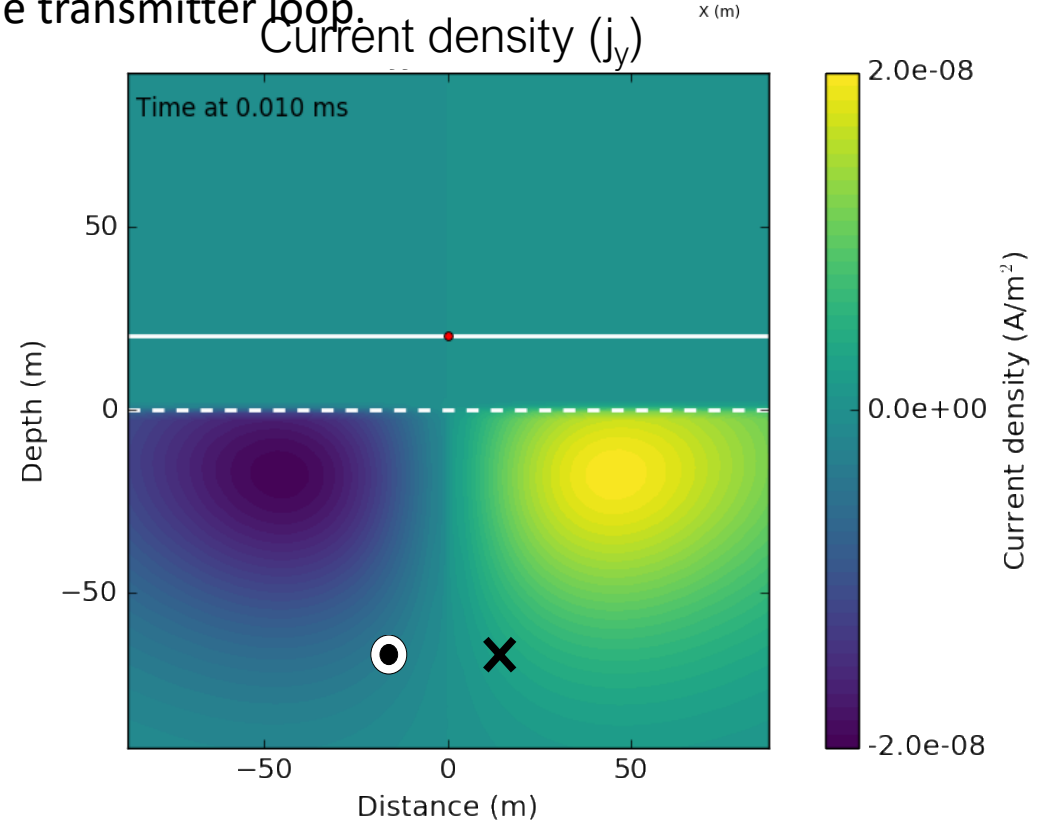
Current Density

- Time: 0.01ms

The nature wants to preserve the magnetic field produced by the current in the transmitter loop so desperately that it creates an induced current that looks like the current in the transmitter loop.



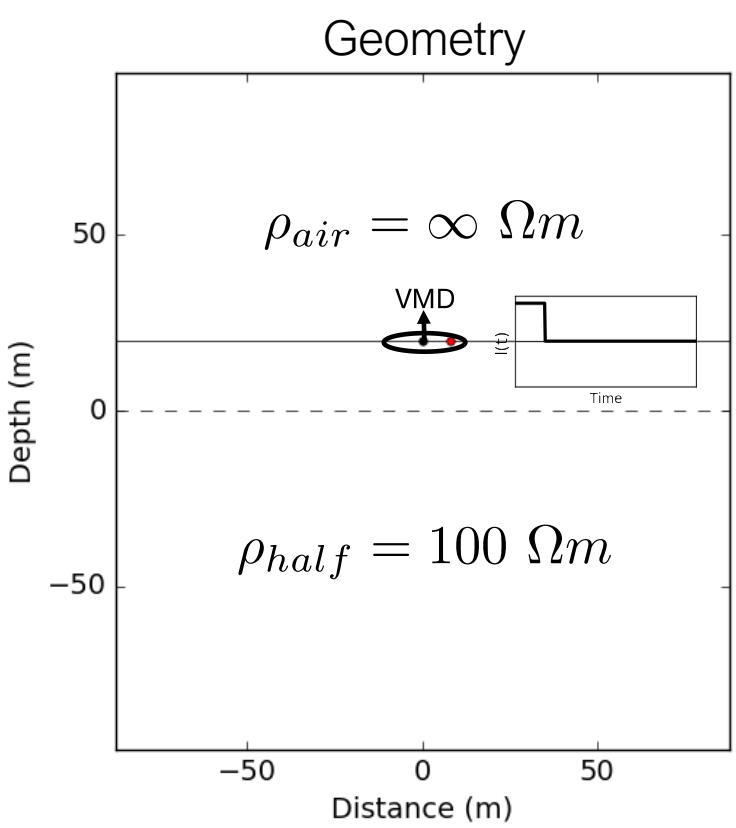


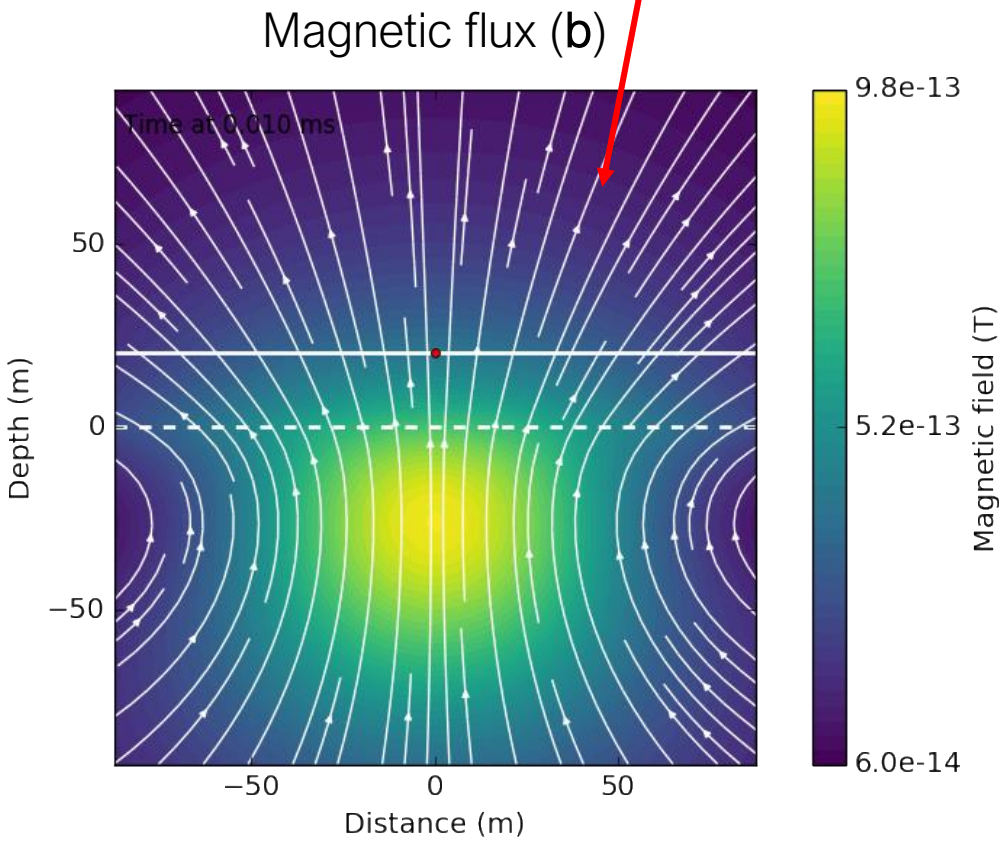


Magnetic flux density

- Time: 0.01ms

This magnetic field is purely from the induced current (has nothing to do with the subsurface magnetization)





Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

$$d = 1260\sqrt{t\rho}$$

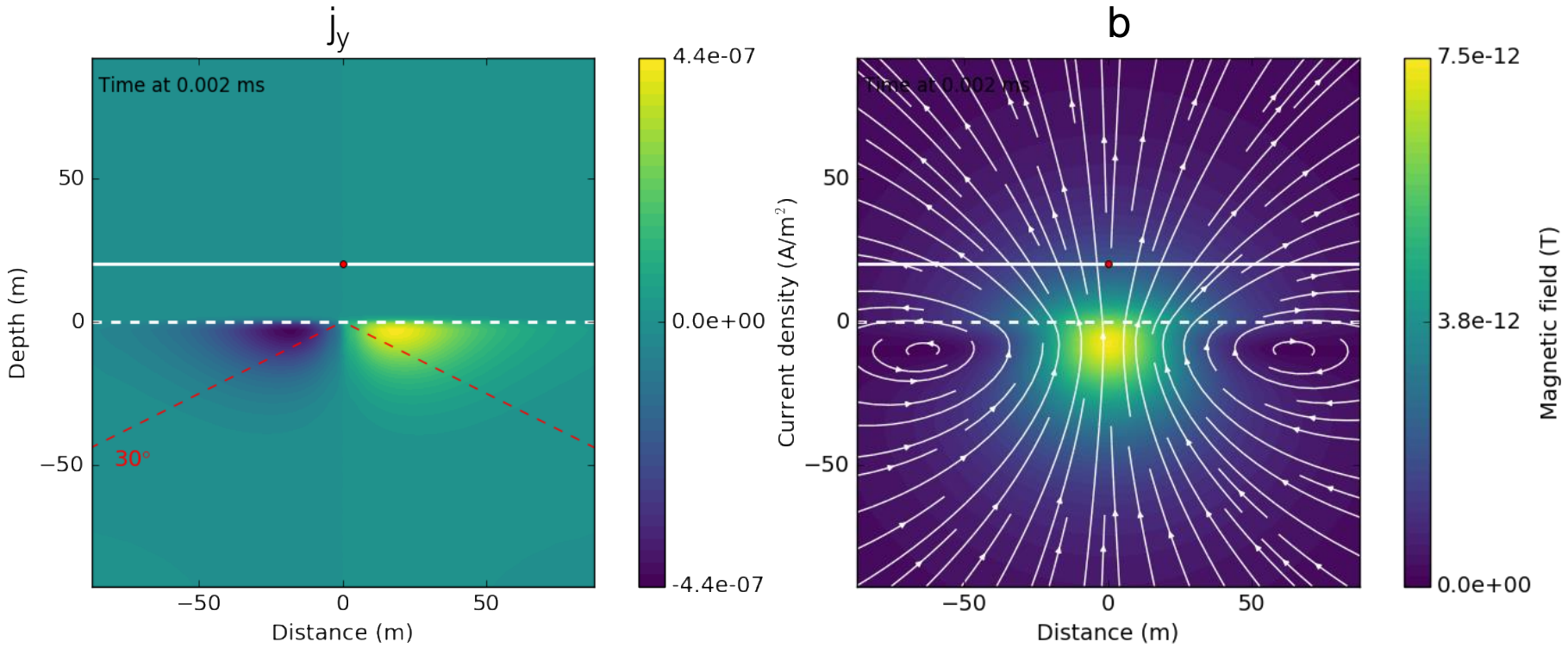


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

$$d = 1260\sqrt{t\rho}$$

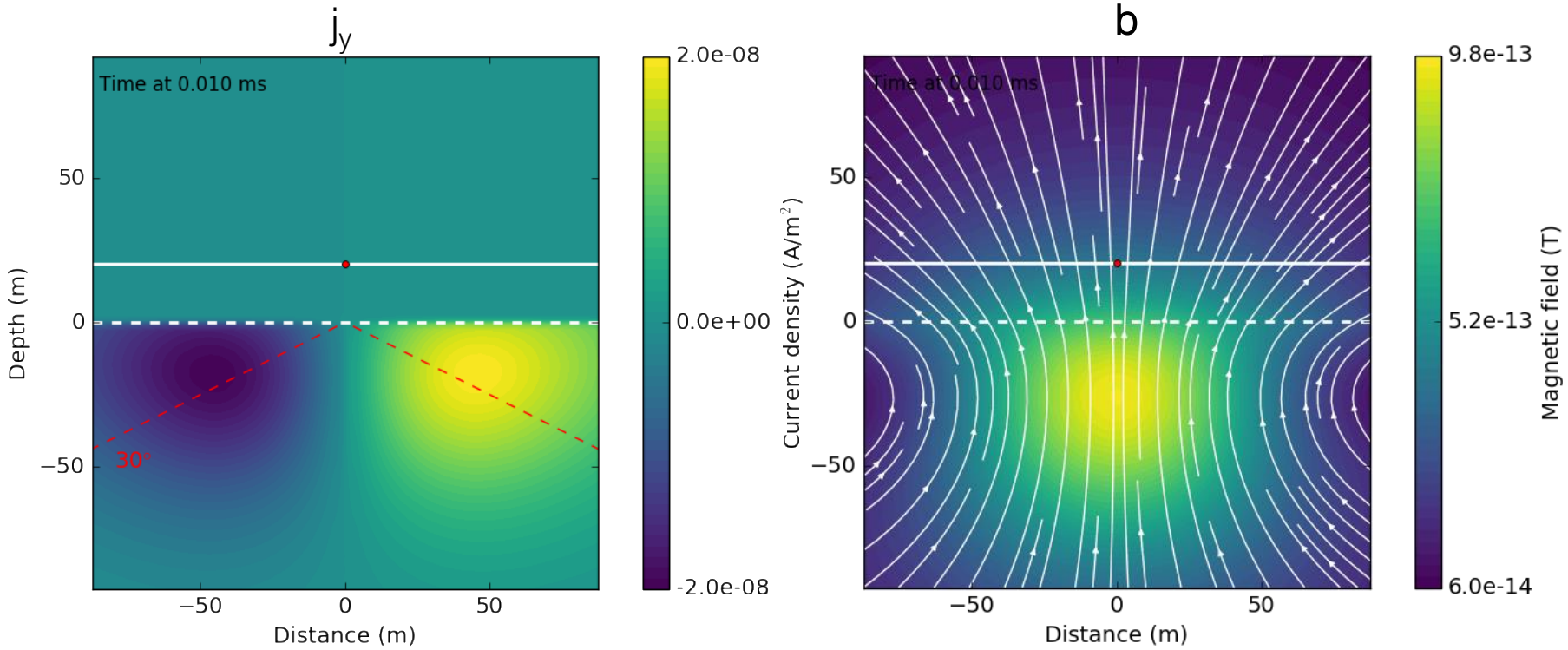
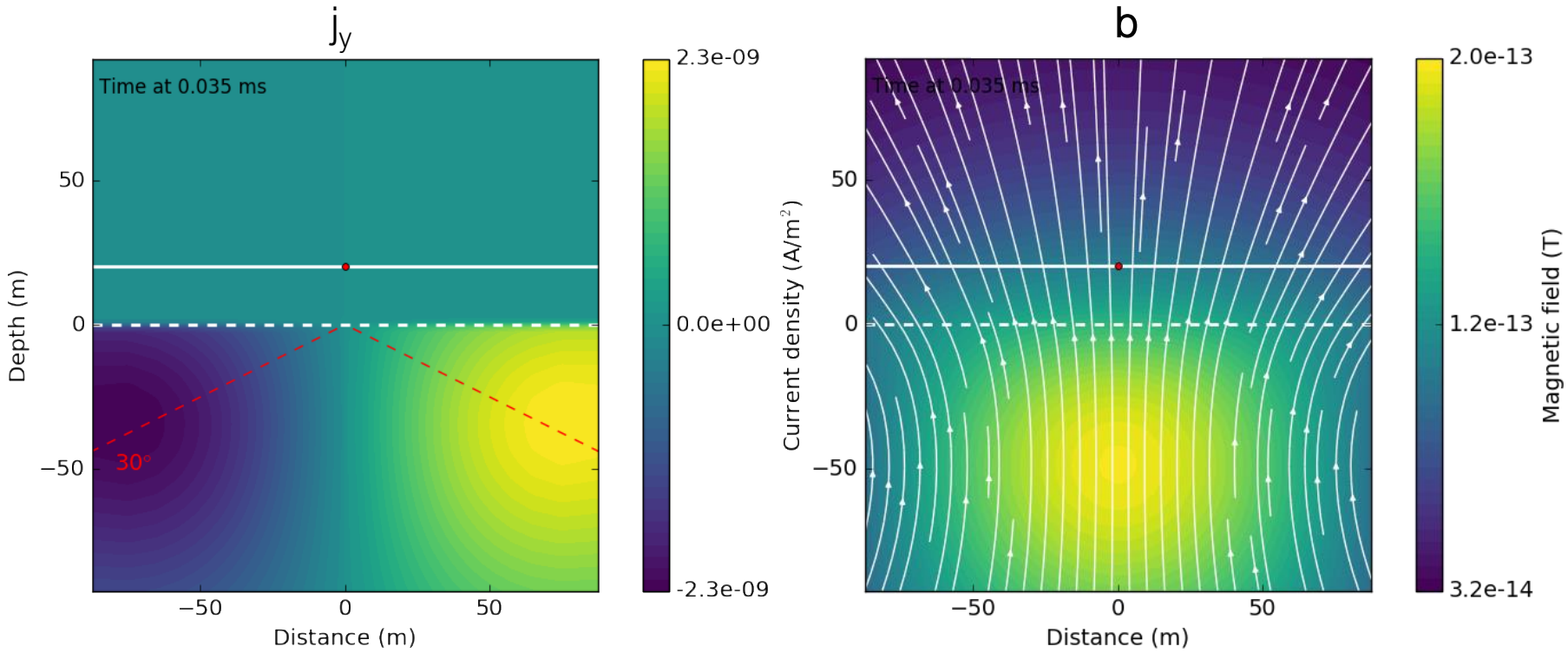


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

$$d = 1260\sqrt{t\rho}$$



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Propagation through time

- Time: 0.110ms
- diffusion distance = 132 m

$$d = 1260\sqrt{t\rho}$$

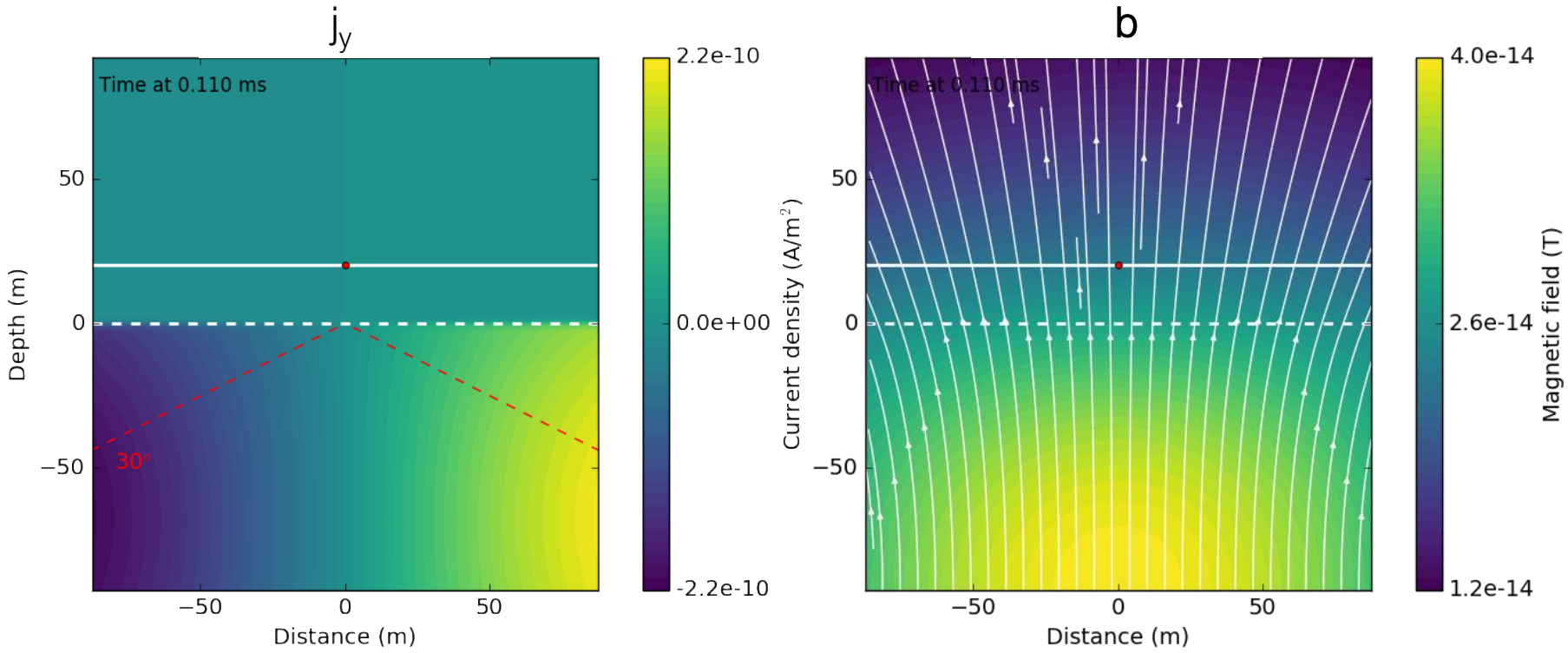
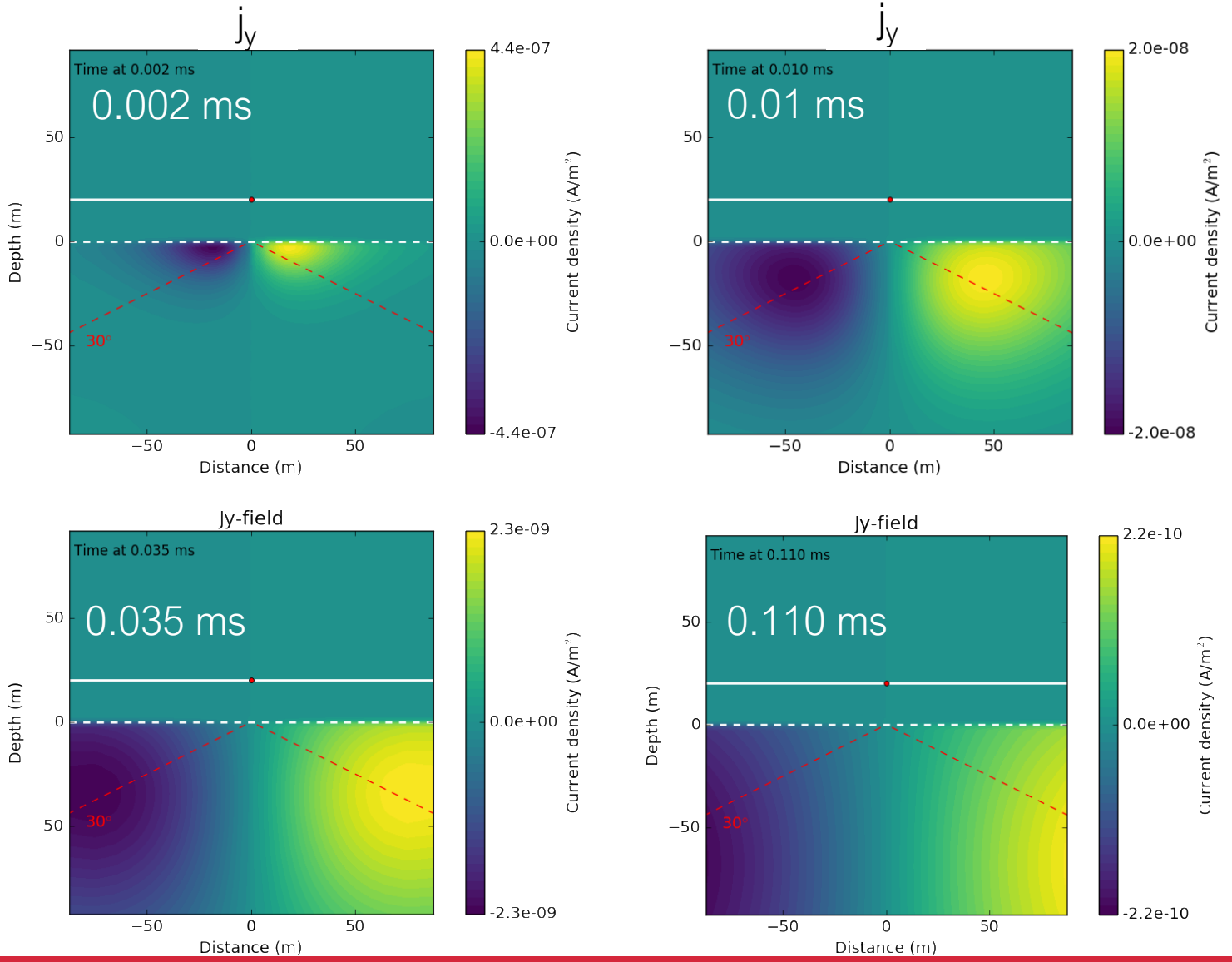
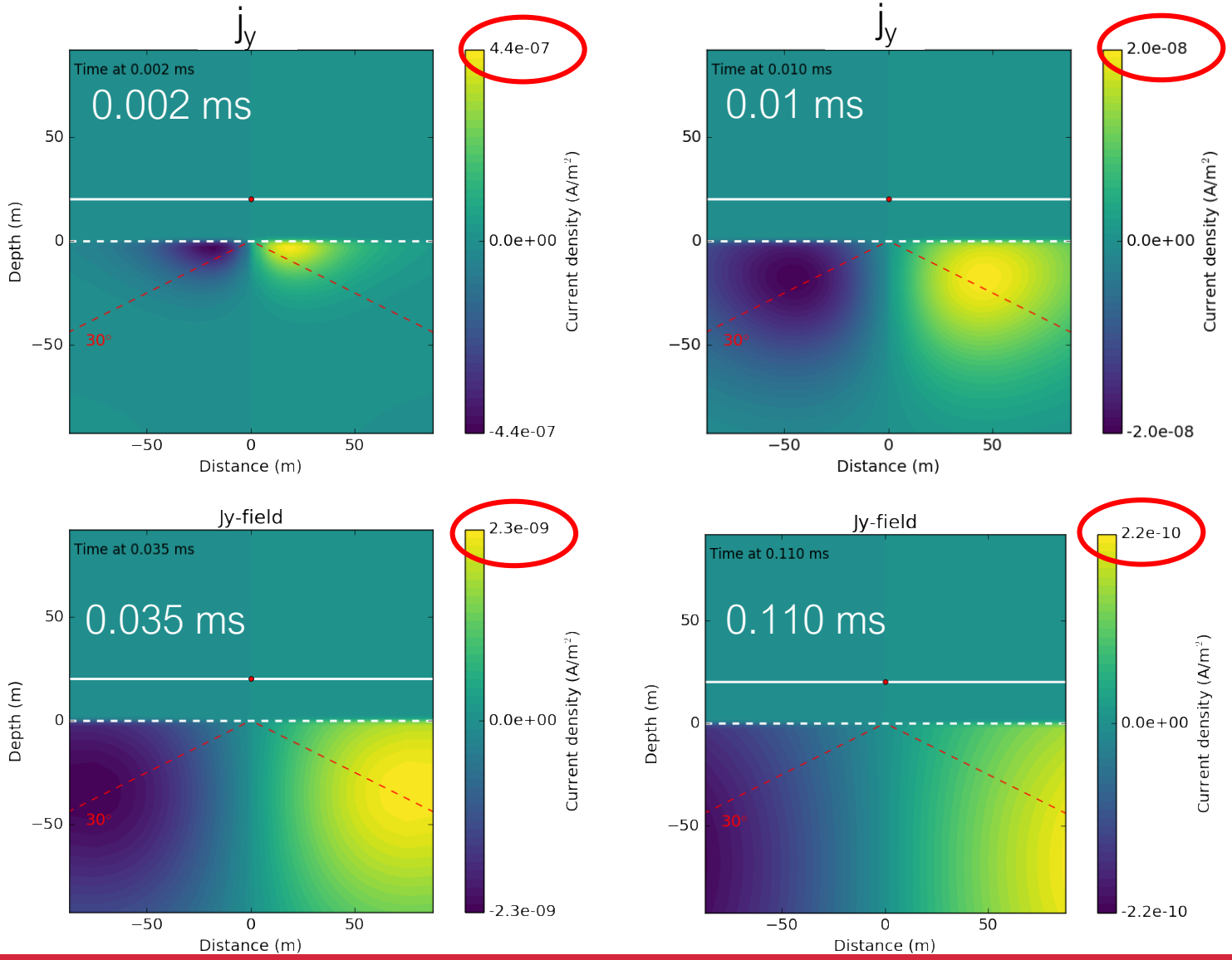


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Summary: propagation through time



Summary: propagation of current through time

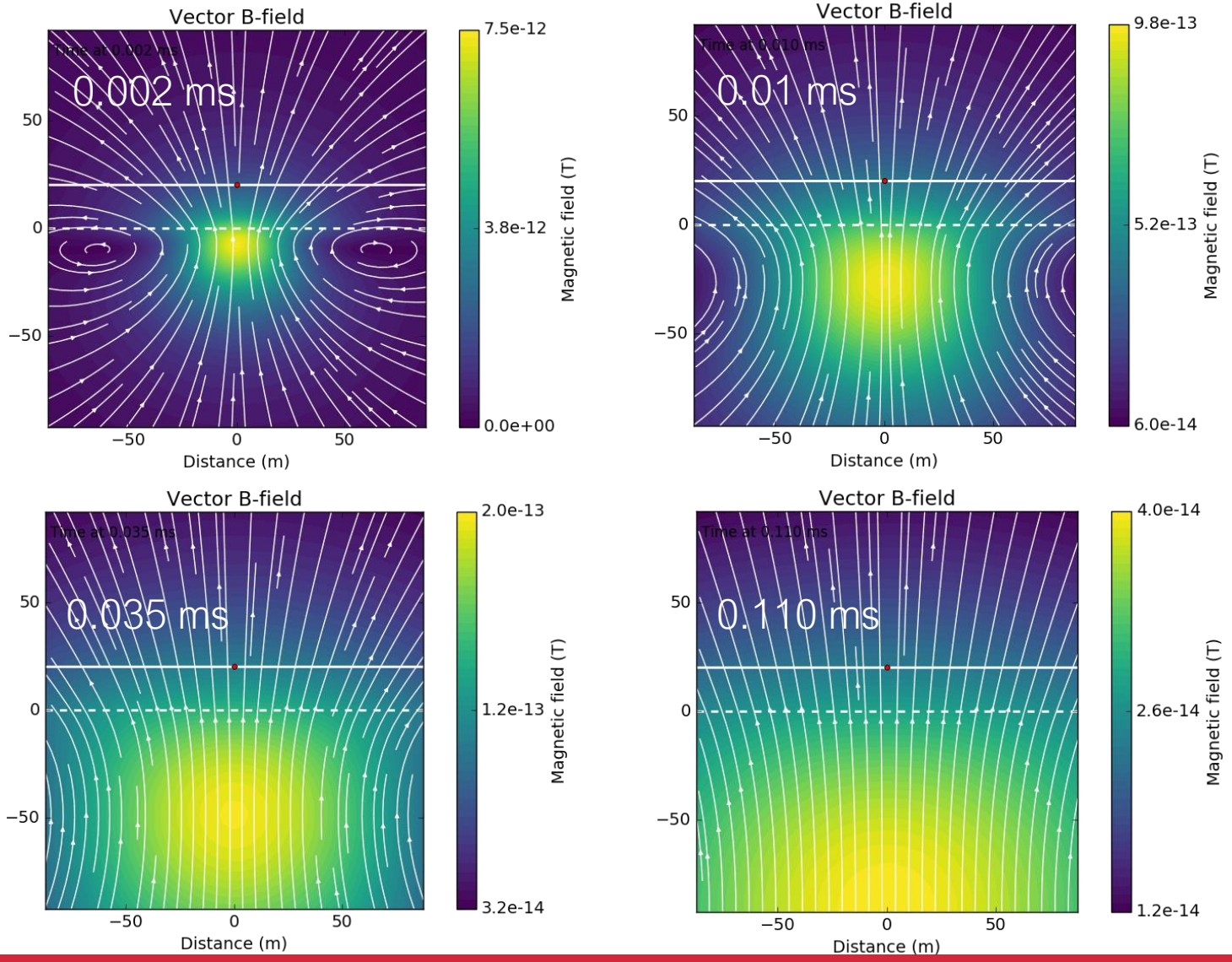


Observation

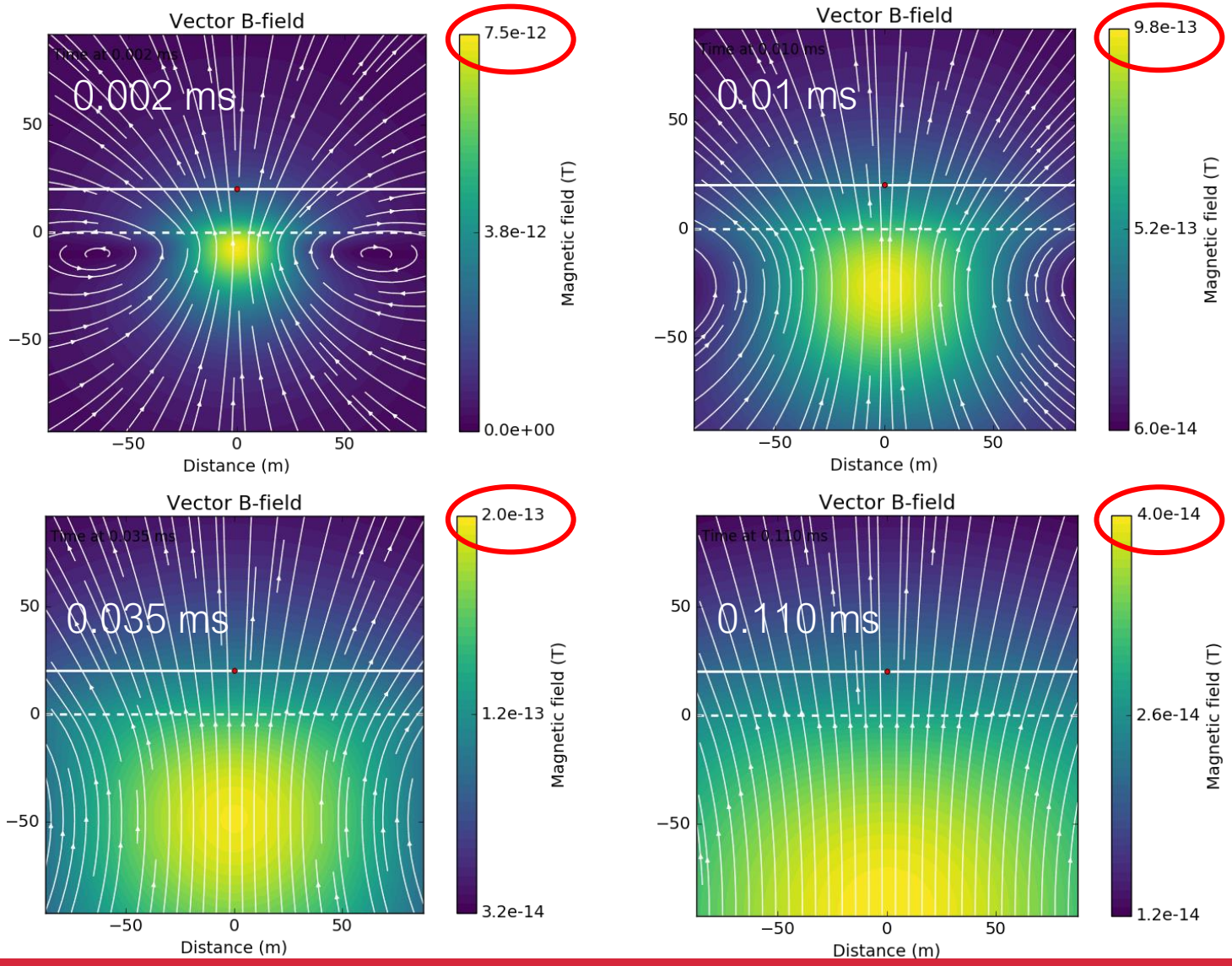
- The current propagates downward and outward.
- The current becomes smaller and smaller when propagating.
- The current becomes more and more diffused (i.e., less and less focused)

diffusion

Propagation of magnetic field through time



Propagation of magnetic field through time



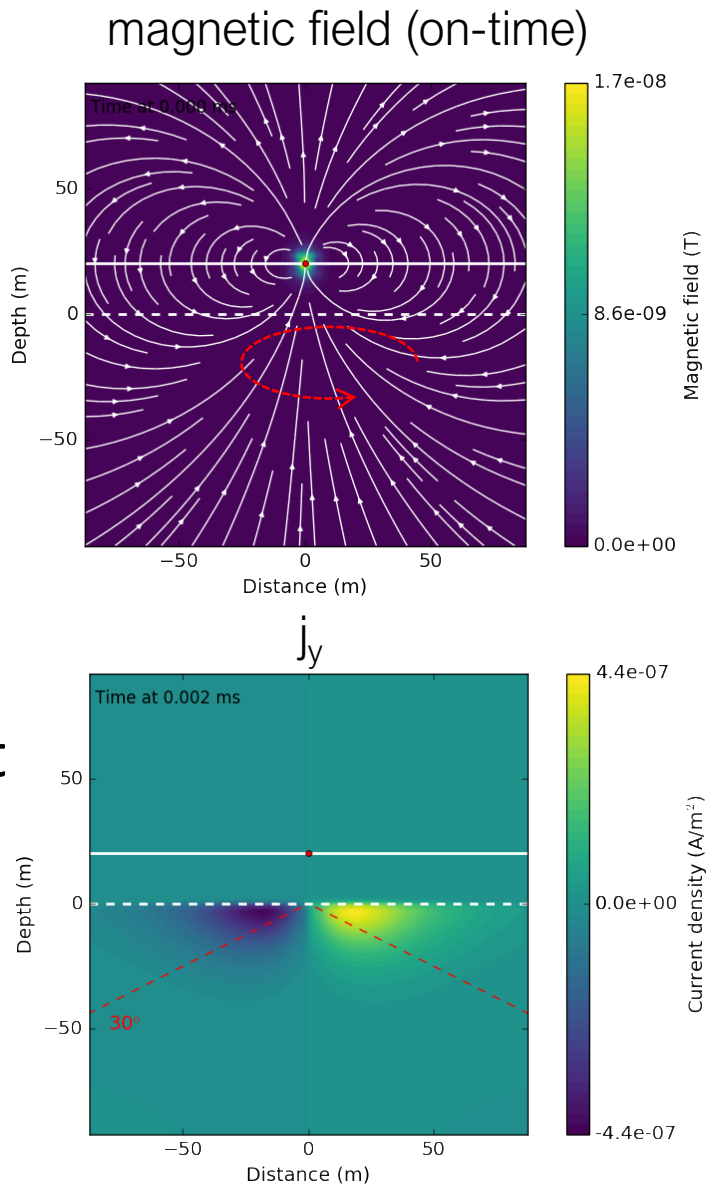
Observation

- The magnetic field propagates downward and outward.
- The magnetic field becomes smaller and smaller when propagating.
- The magnetic field becomes more and more diffused (i.e., less and less focused)

diffusion

Important points

- Currents flow in same plane as transmitter currents
- Currents diffuse outward downward
- Each transmitter has a “footprint”
- Max resolution controlled by earliest time
- Depth of investigation controlled by latest time



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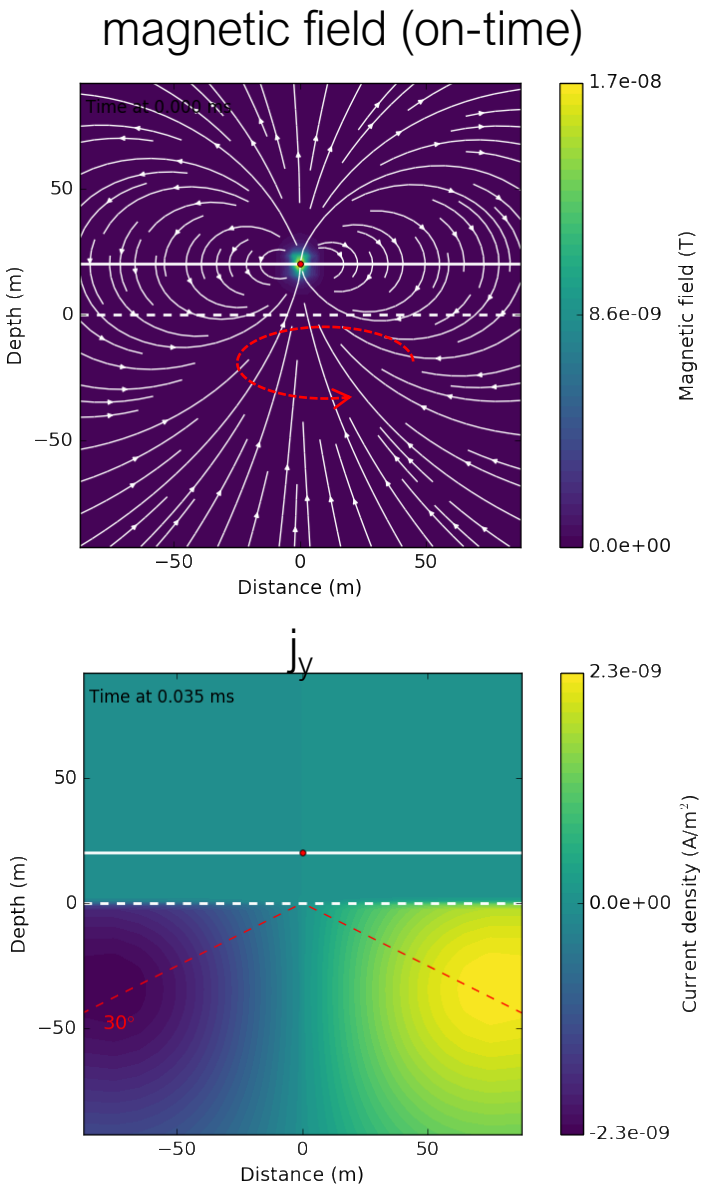
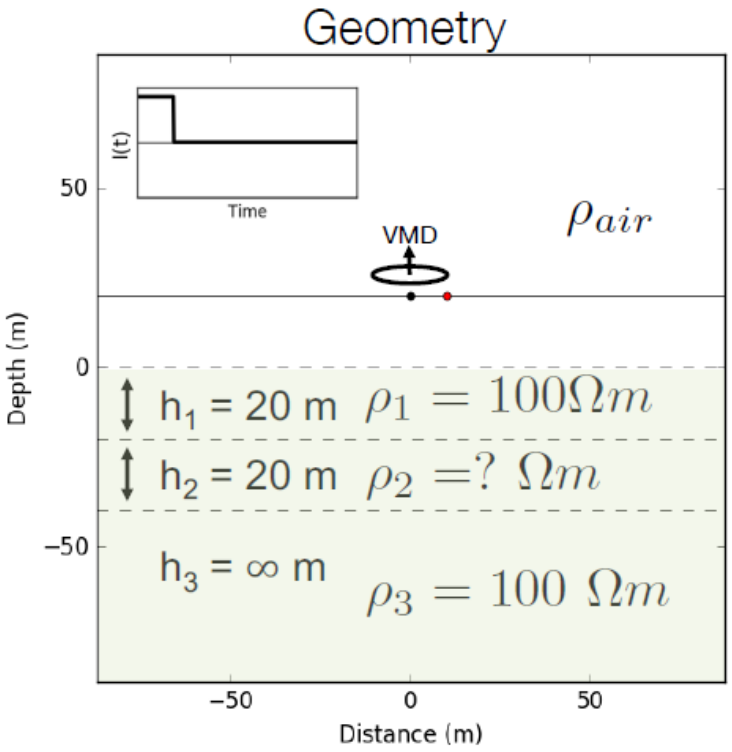


Layered earth model

- 3 layers + air,
- ρ_2 varies



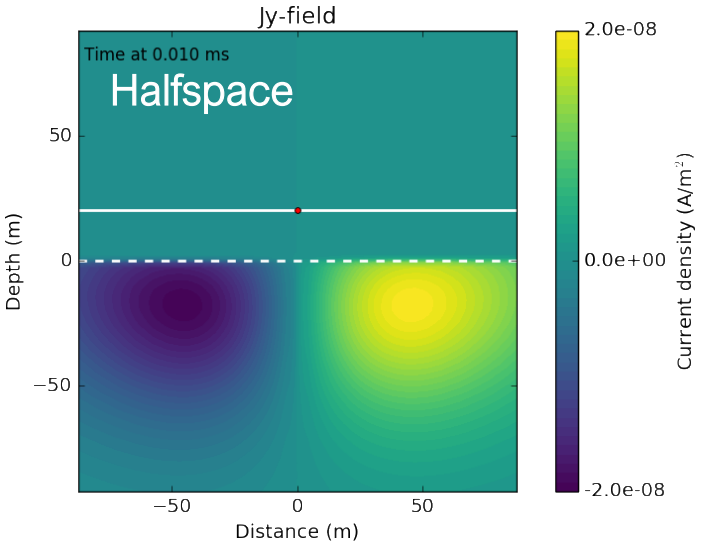
- Four different cases:
  - Halfspace
    ρ_2 = 100 Ωm
  - Resistive
    ρ_2 = 1000 Ωm
  - Conductive
    ρ_2 = 10 Ωm
  - Very conductive
    ρ_2 = 1 Ωm

- Fields
  - j_y off-time
  - b off-time

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

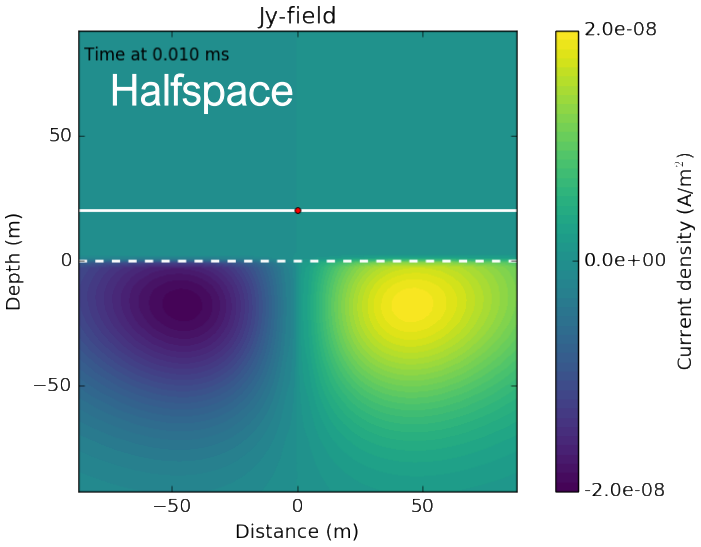
Layered earth currents (j_y)

ρ_2 = 100 Ωm



Layered earth currents (j_y)

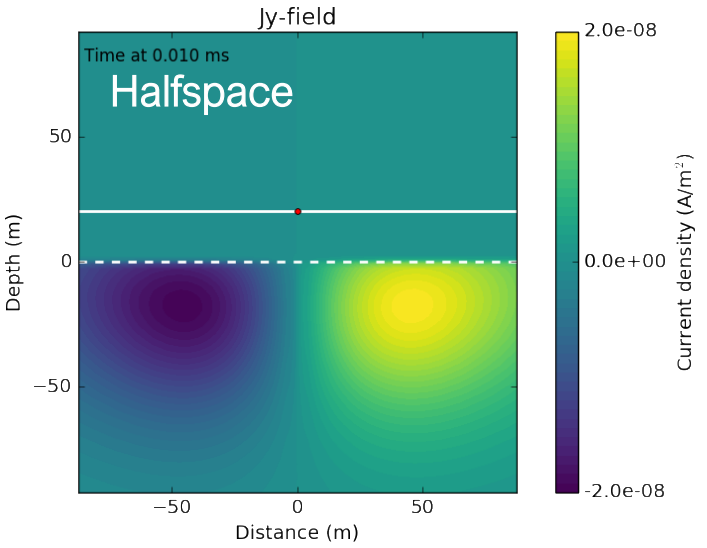
ρ_2 = 100 Ωm



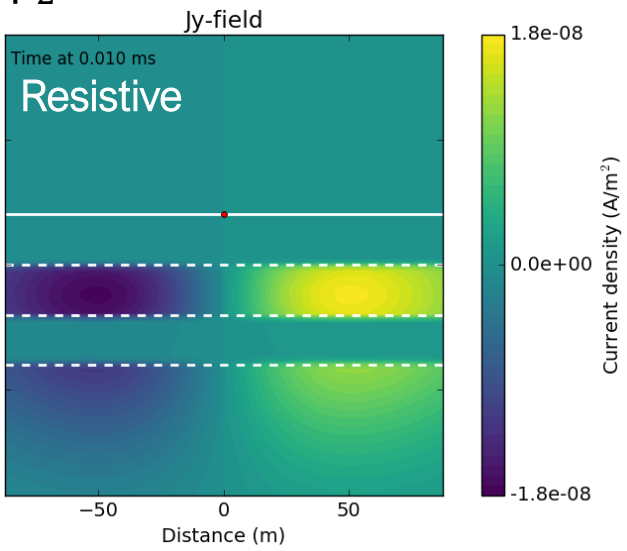
ρ_2 = 1000 Ωm

Layered earth currents (j_y)

ρ_2 = 100 Ωm

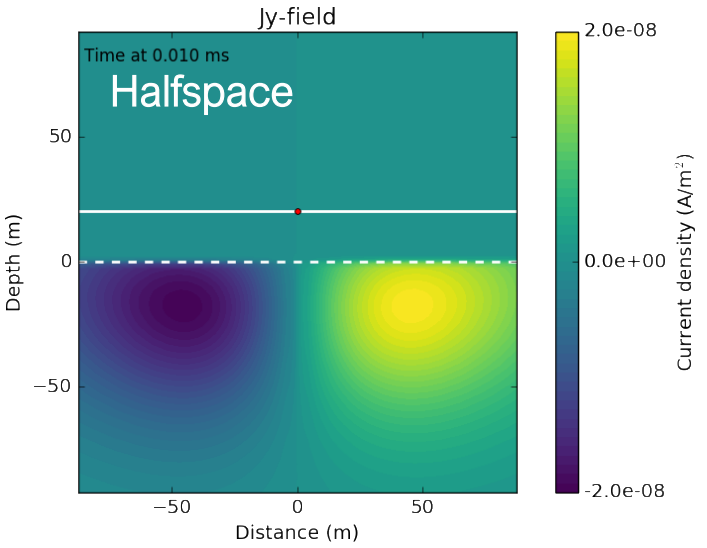


ρ_2 = 1000 Ωm

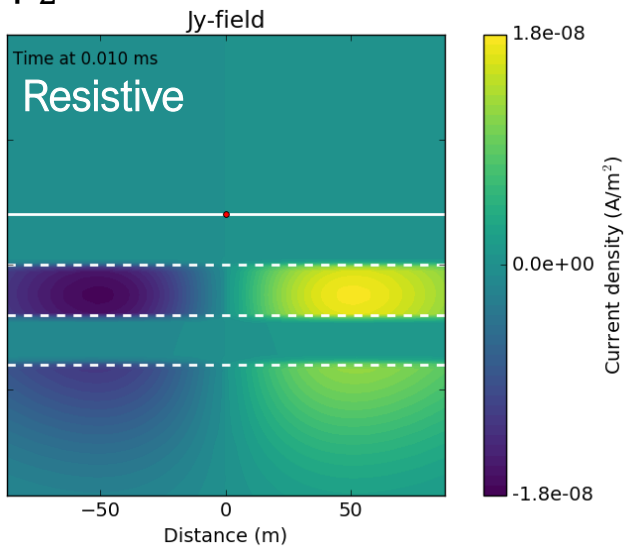


Layered earth currents (j_y)

ρ_2 = 100 Ωm



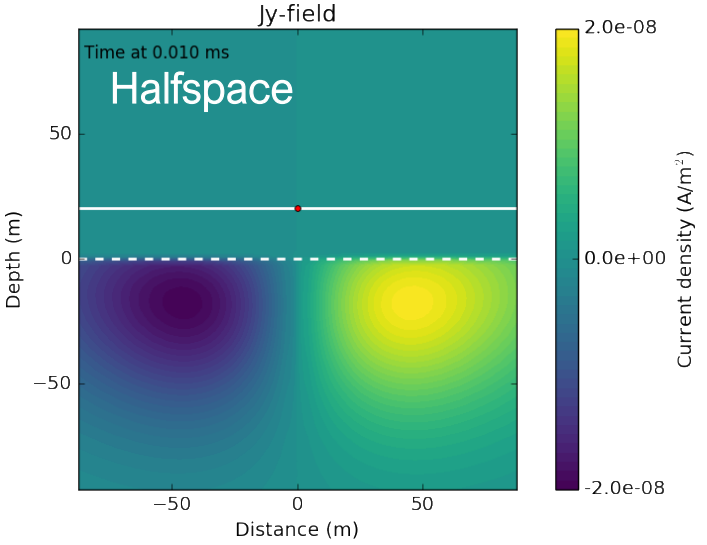
ρ_2 = 1000 Ωm



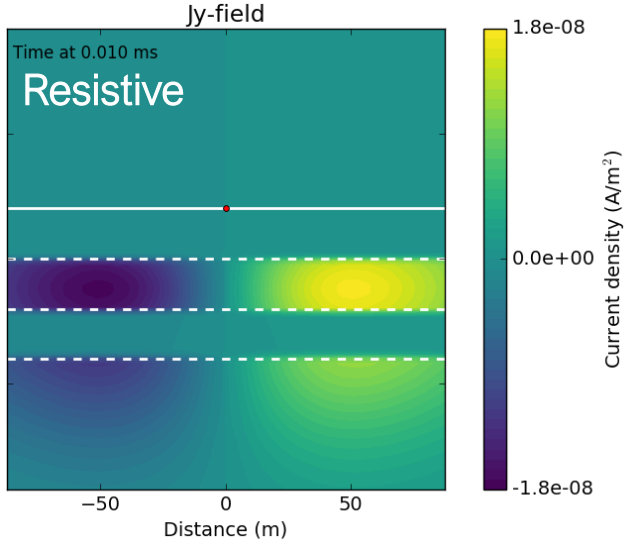
ρ_2 = 10 Ωm

Layered earth currents (j_y)

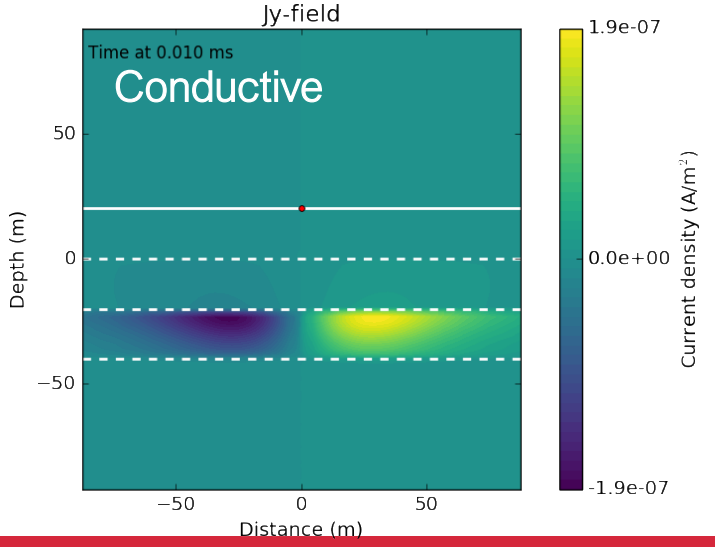
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm

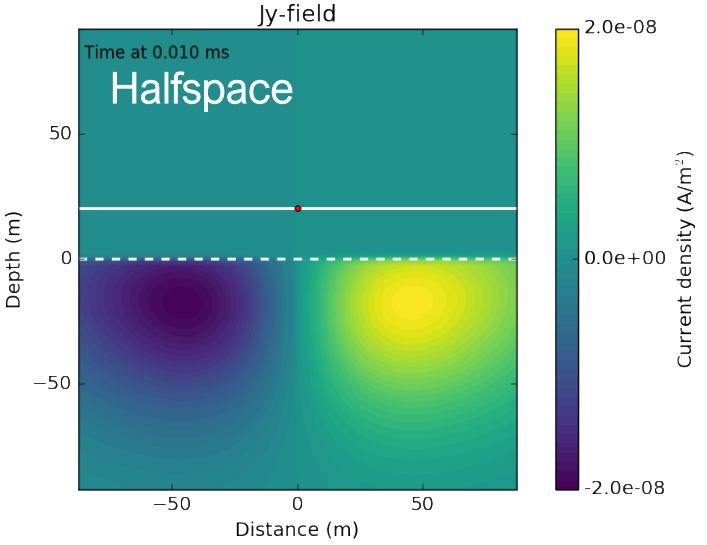


ρ_2 = 10 Ωm

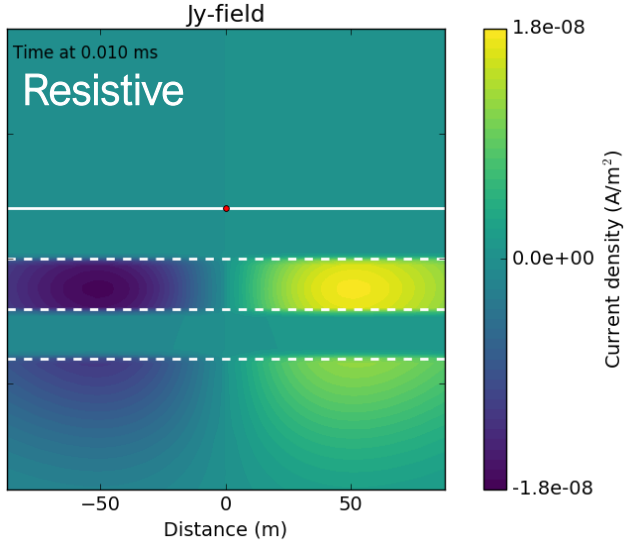


Layered earth currents (j_y)

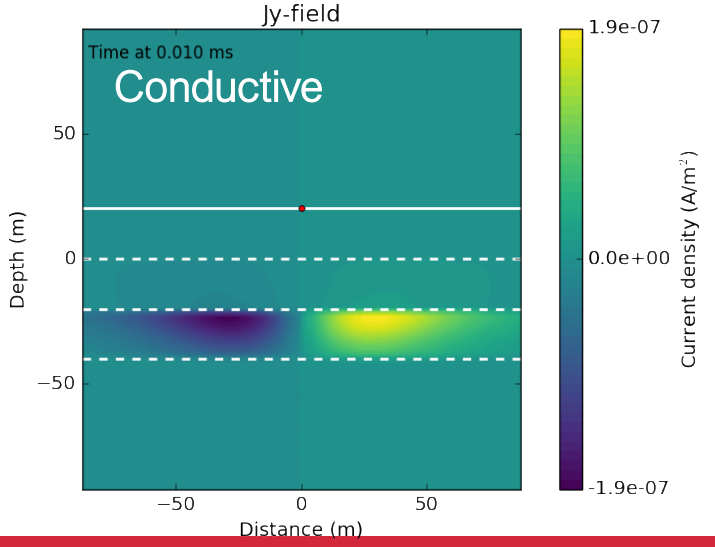
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm

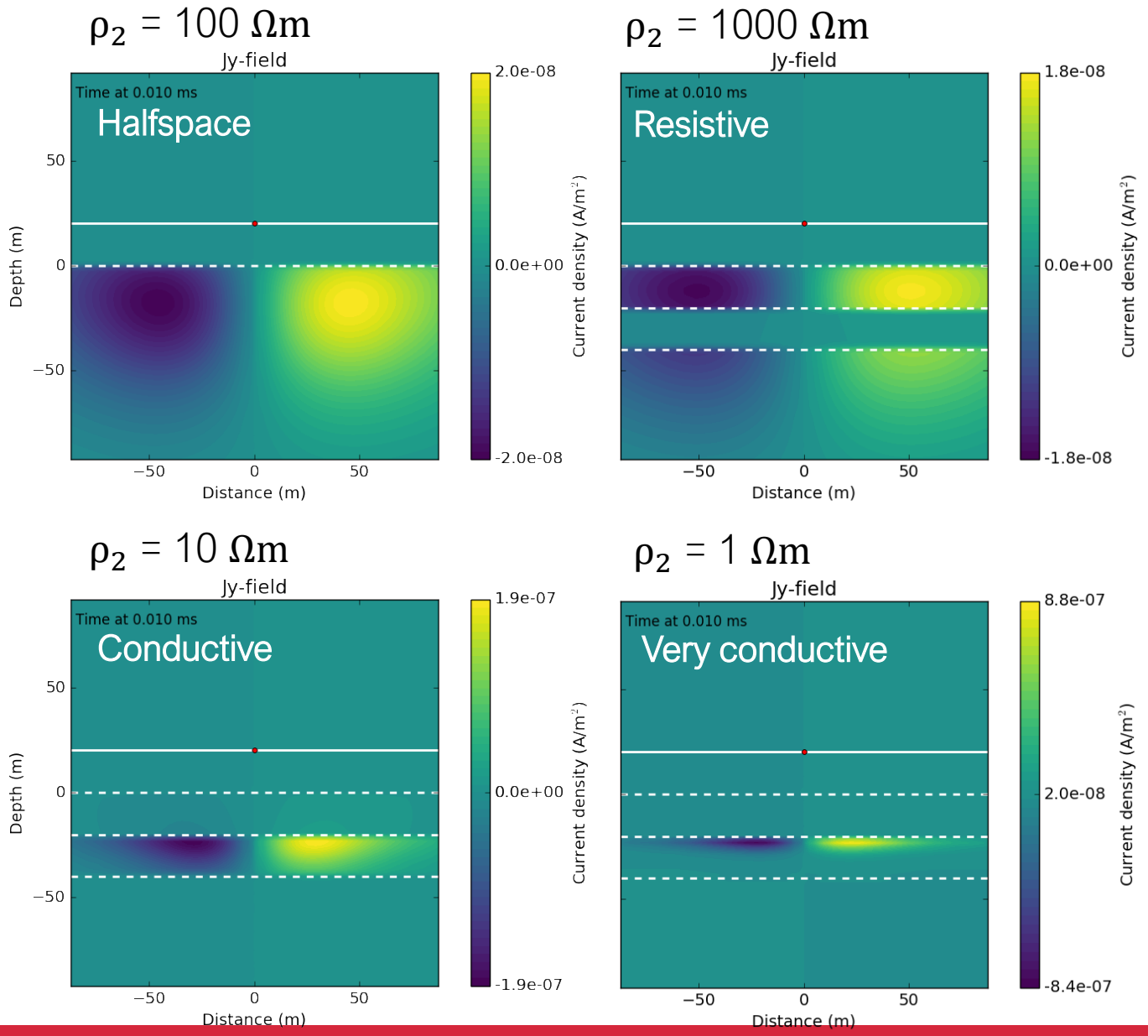


ρ_2 = 10 Ωm

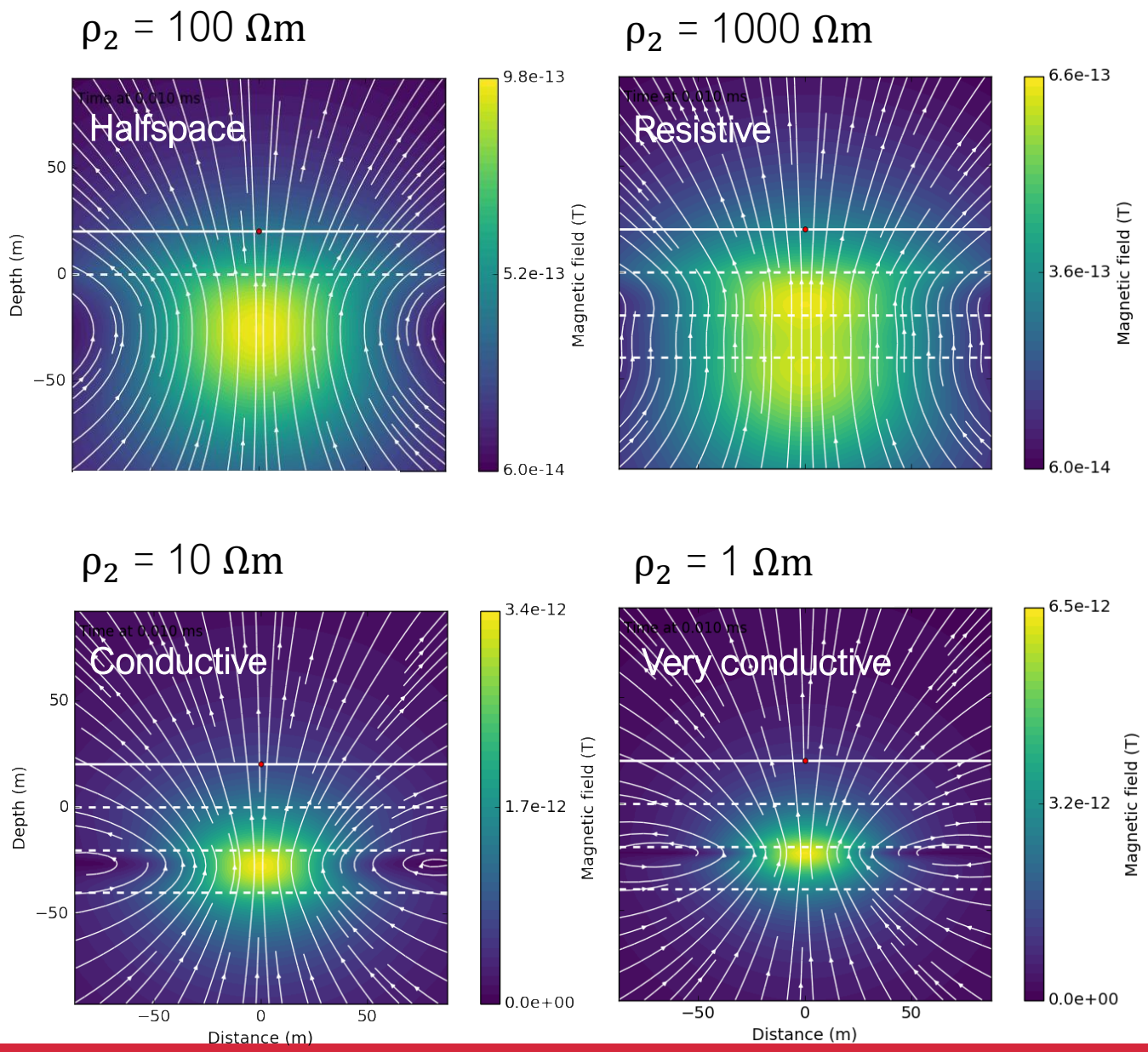


ρ_2 = 1 Ωm

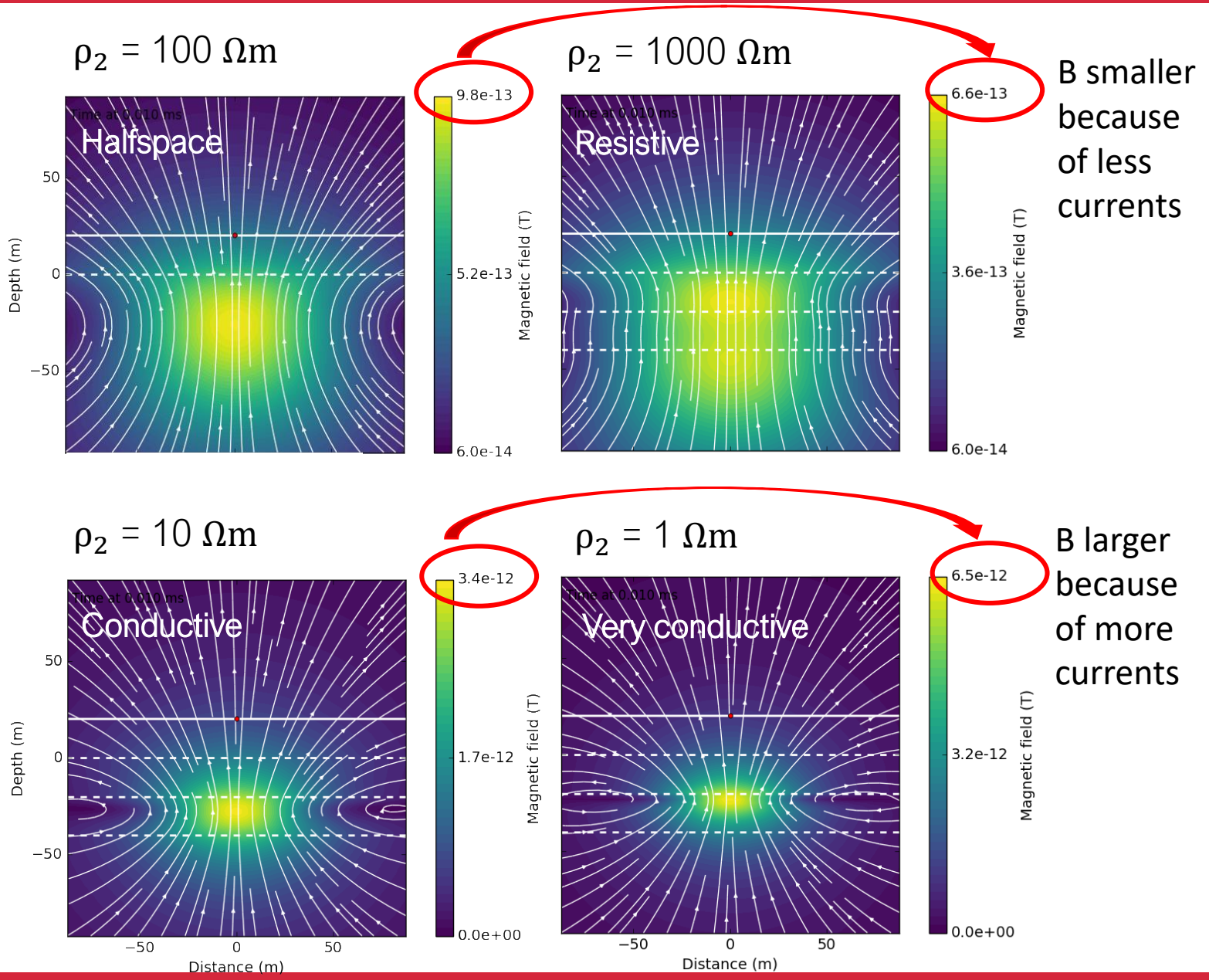
Layered earth currents (j_y)



Layered earth mag. fields (b)

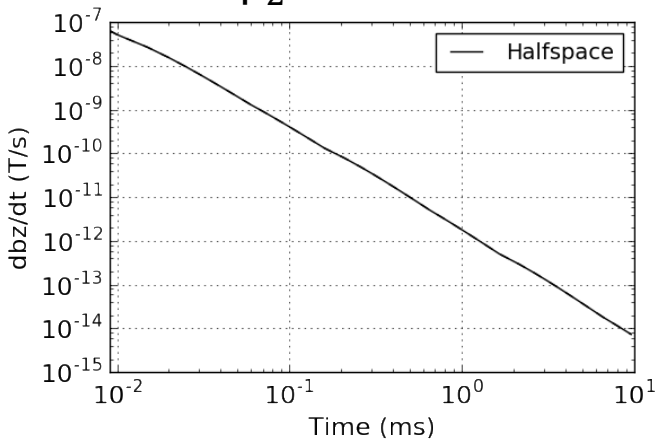


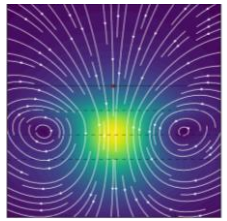
Layered earth mag. fields (b)



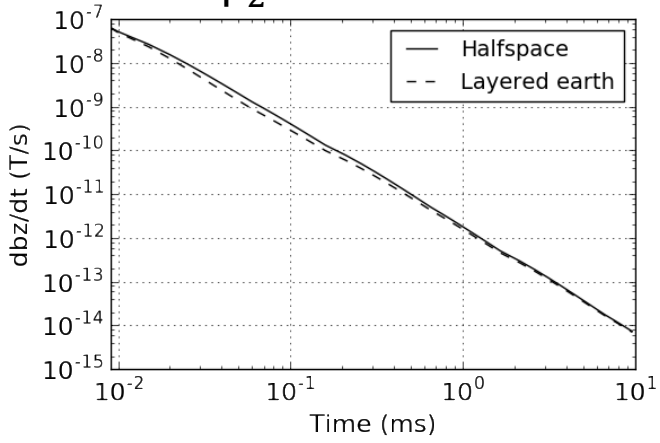
db_z/dt sounding curves

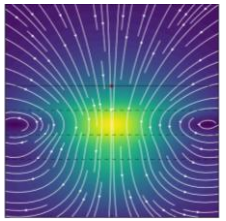
ρ_2 = 100 Ωm



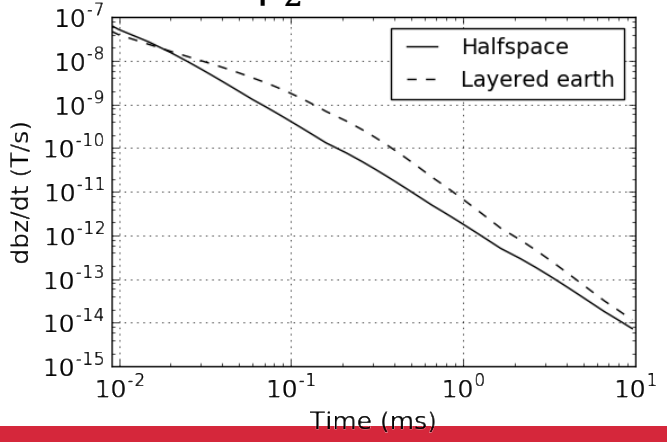


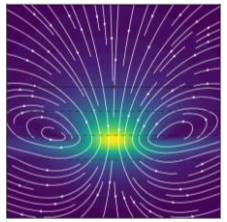
ρ_2 = 1000 Ωm



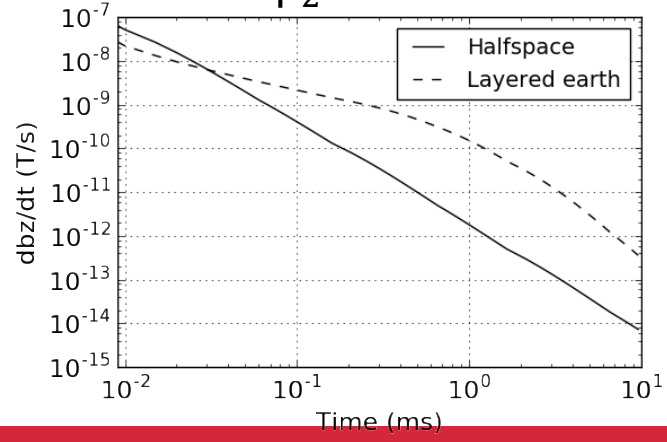


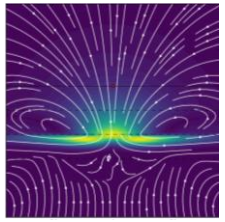
ρ_2 = 10 Ωm





ρ_2 = 1 Ωm

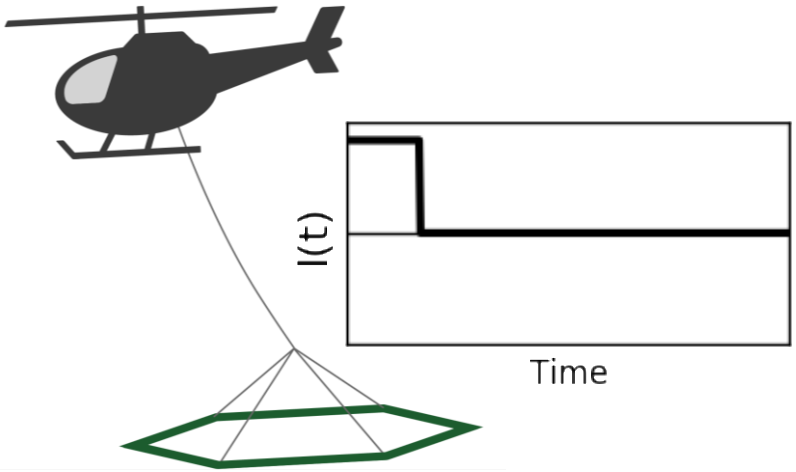




Observations

- EM signal decays slower in more conductive medium
- EM with inductive sources very sensitive to conductors (not so sensitive to resistors)

Synthetic airborne TEM data



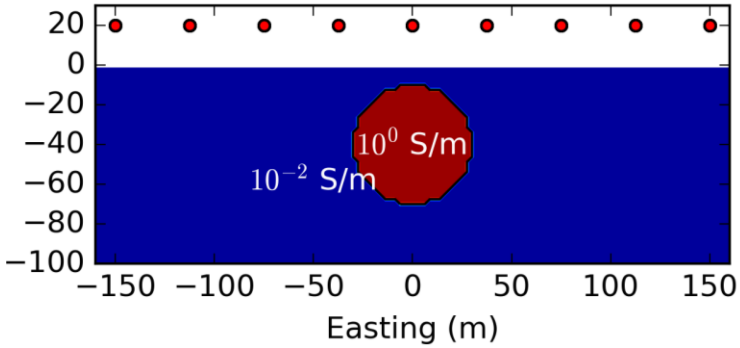
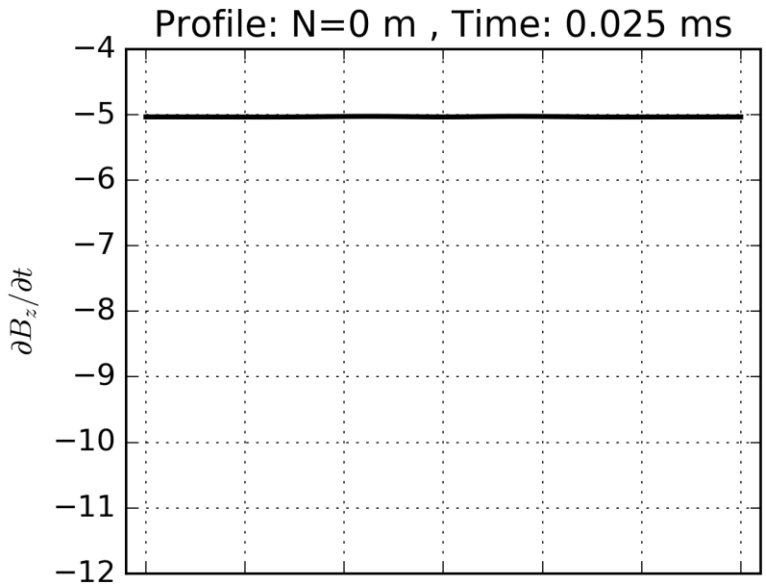


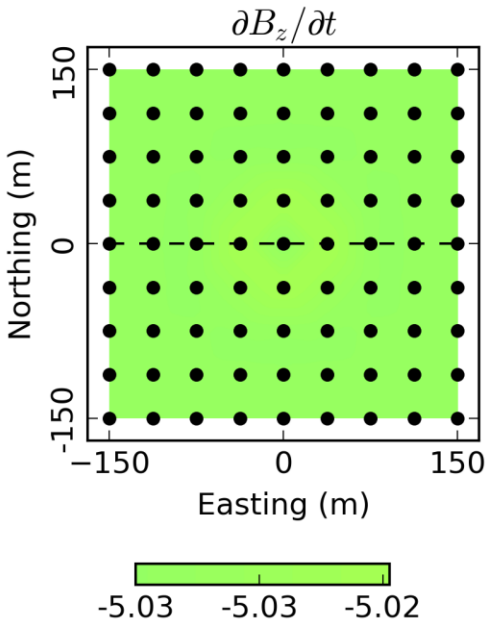
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

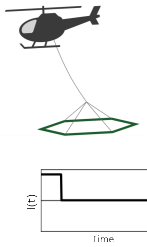
Synthetic airborne TEM data

Data profile



Data map





Conductivity

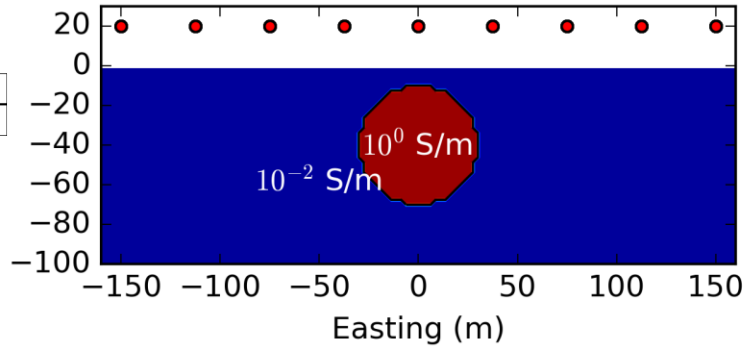
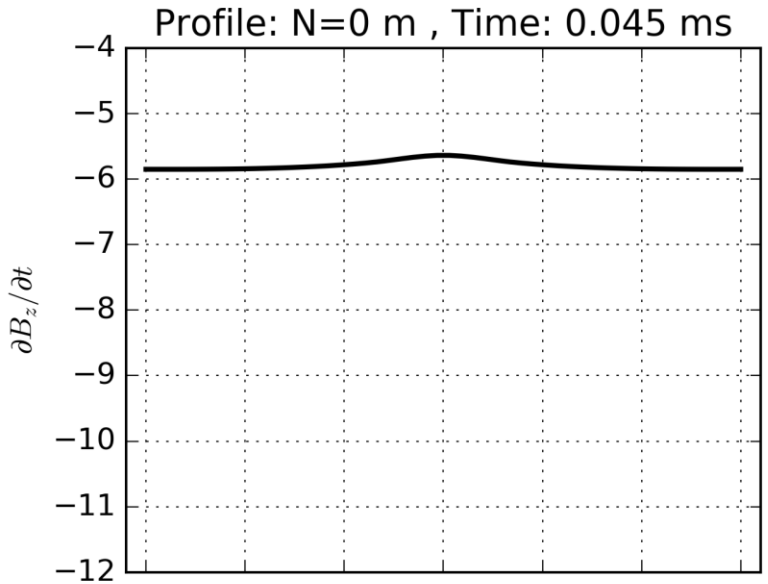


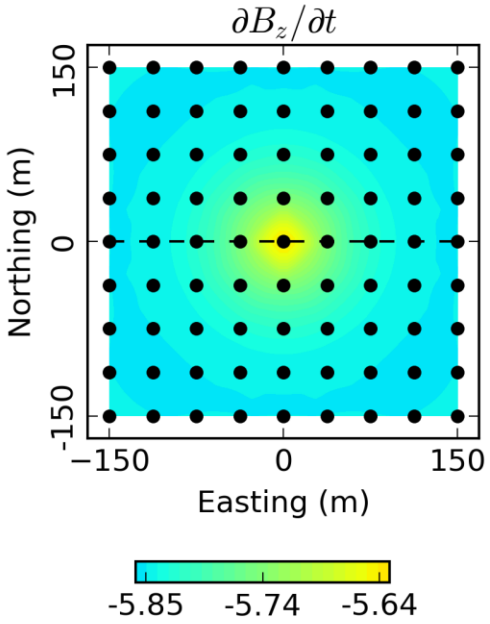
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

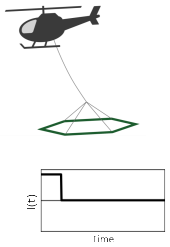
Synthetic airborne TEM data

Data profile



Data map





Conductivity

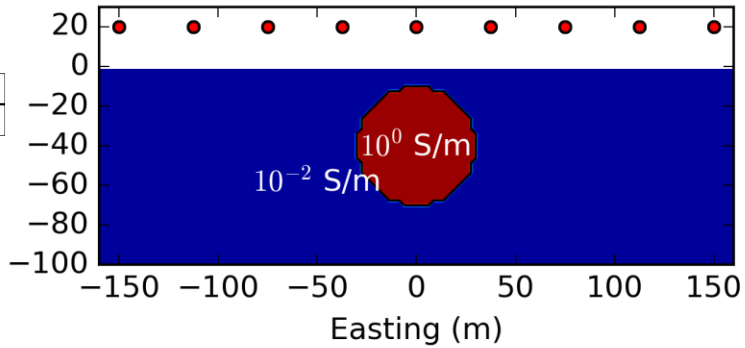
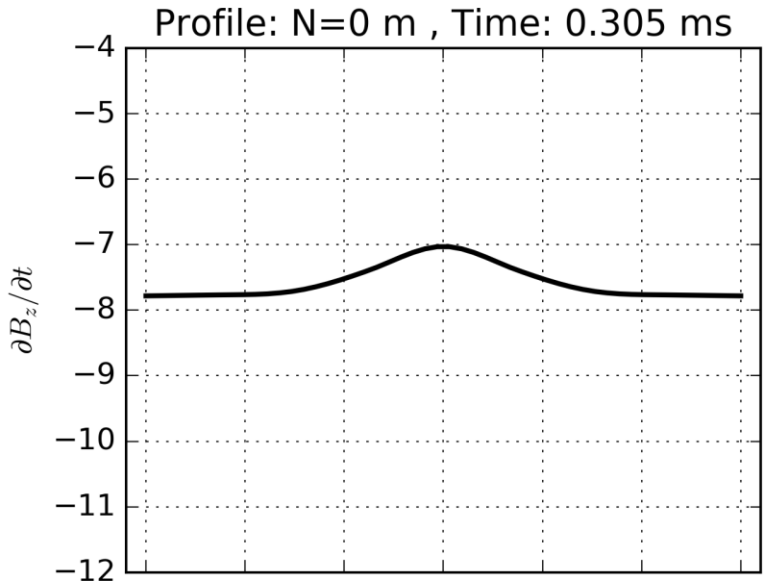


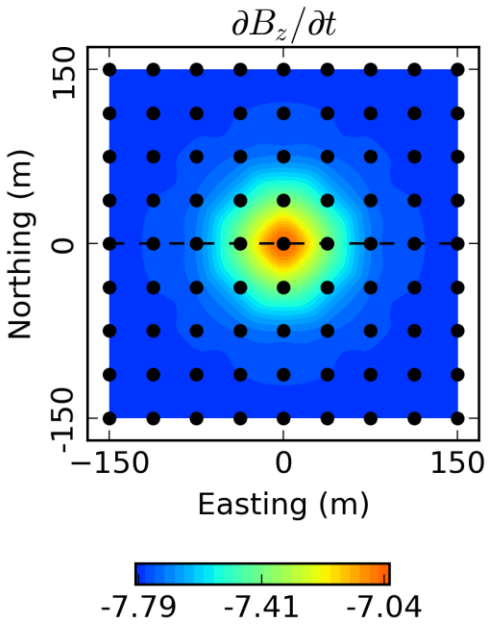
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

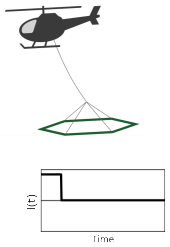
Synthetic airborne TEM data

Data profile



Data map





Conductivity

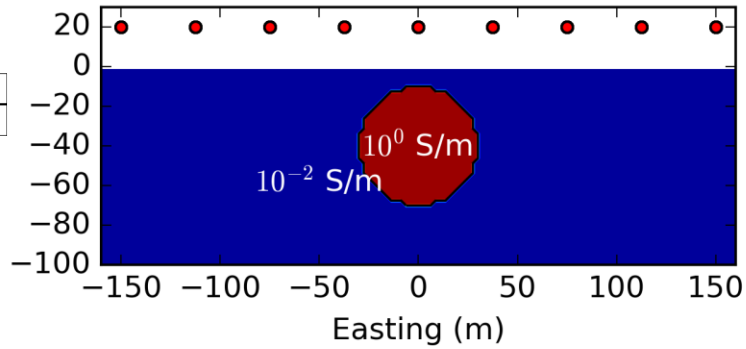
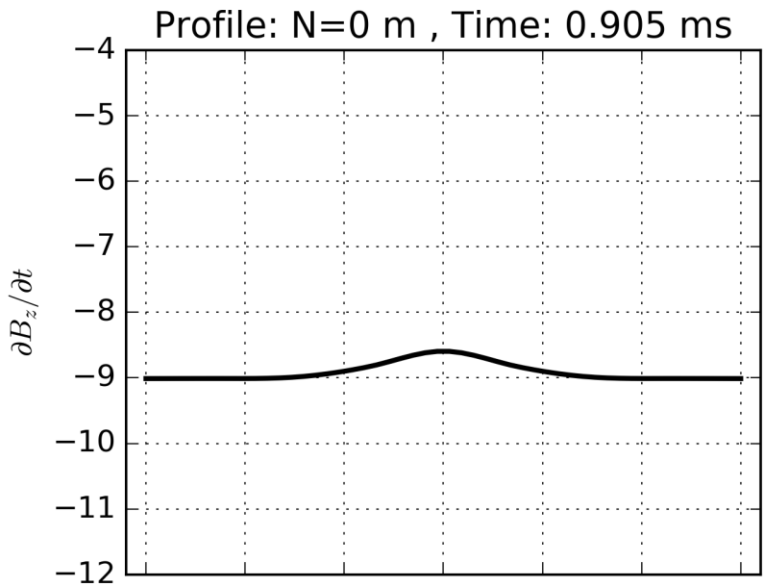


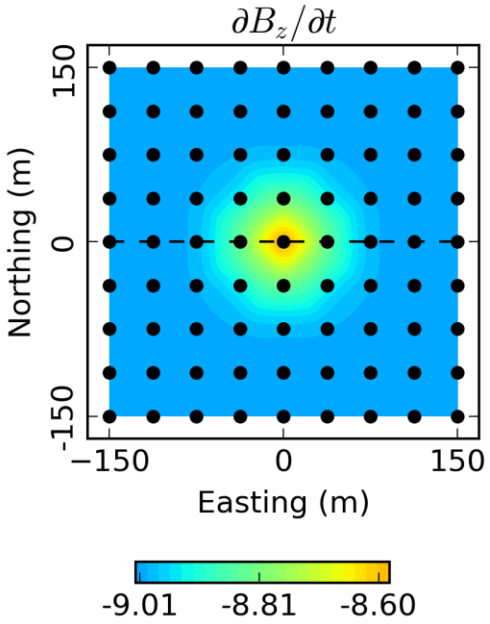
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

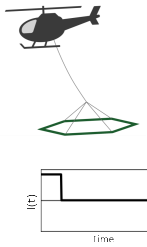
Synthetic airborne TEM data

Data profile



Data map





Conductivity

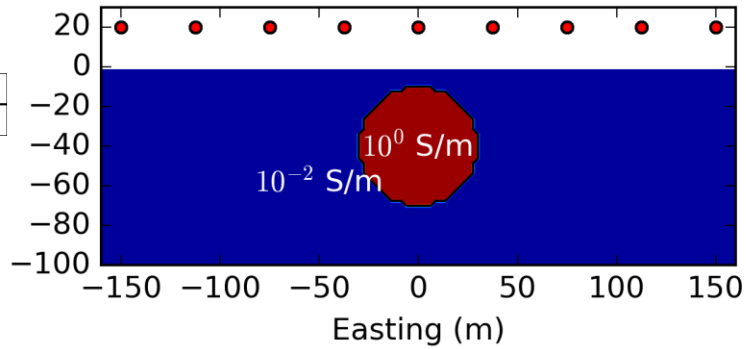
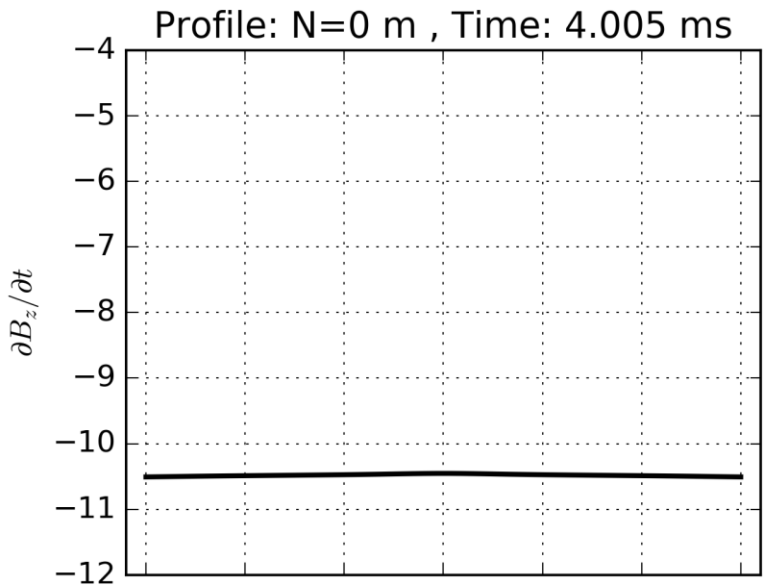


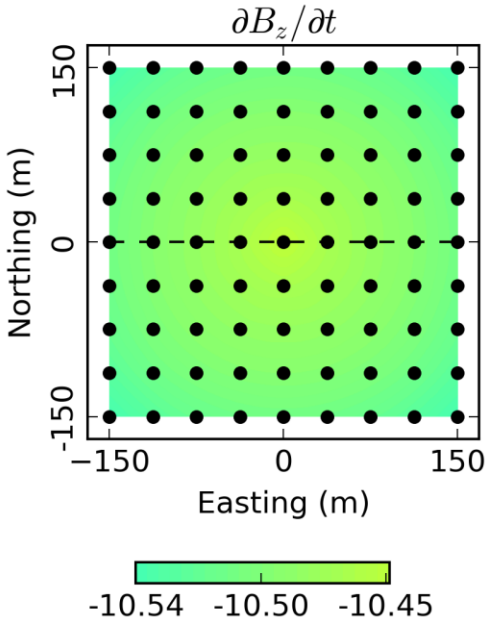
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

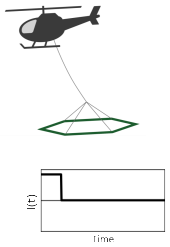
Synthetic airborne TEM data

Data profile



Data map





Conductivity

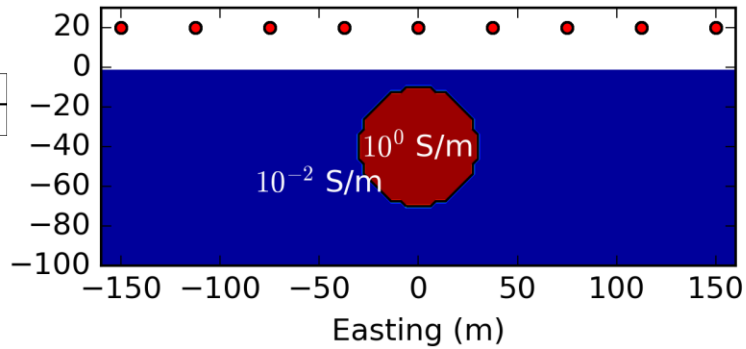
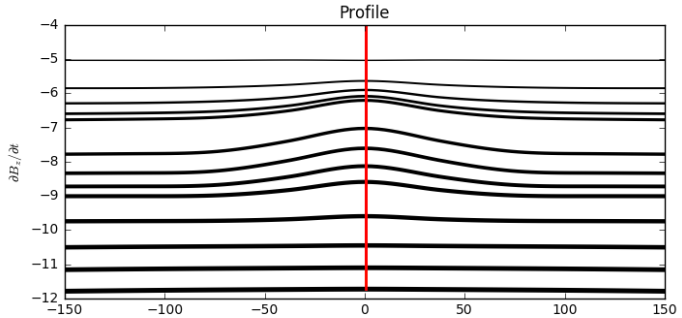
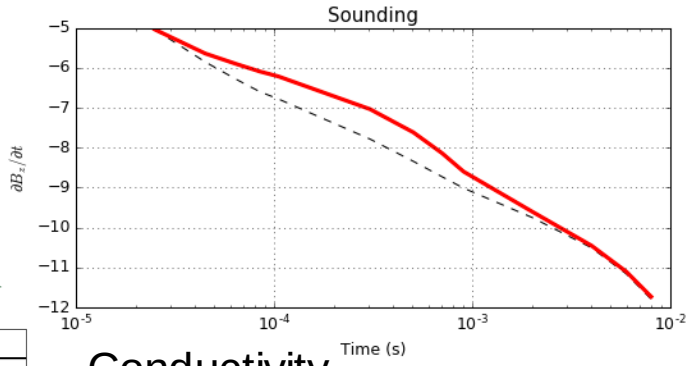
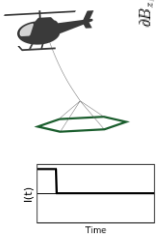


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

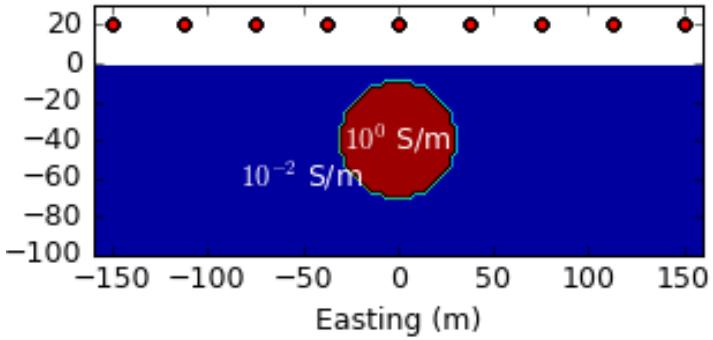
Data profile



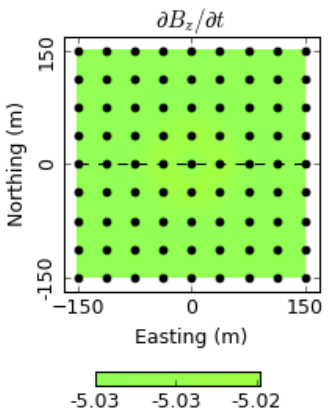




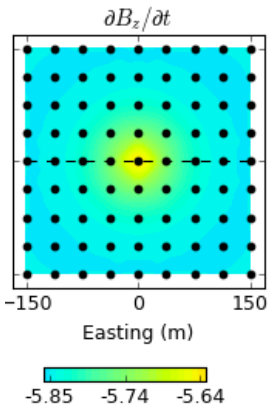
Conductivity



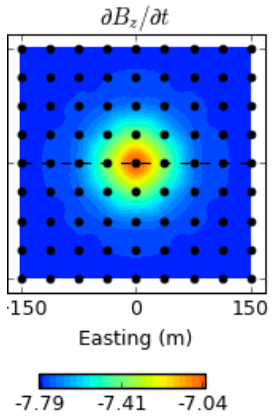
$d = 6$ m
0.025 ms



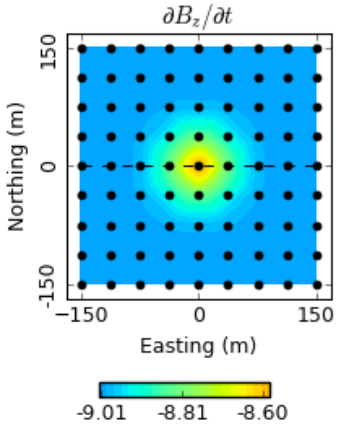
$d = 8$
0.045 ms



$d = 22$
0.305 ms



$d = 38$
0.905 ms



$d = 80$
4.005 ms

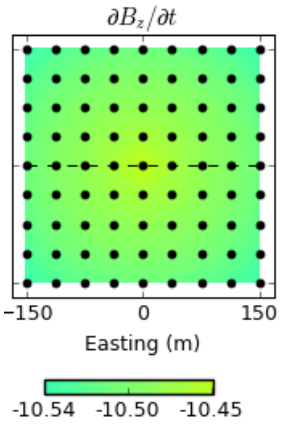


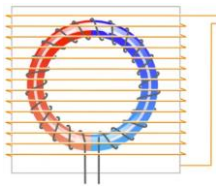
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

TDEM Receiver

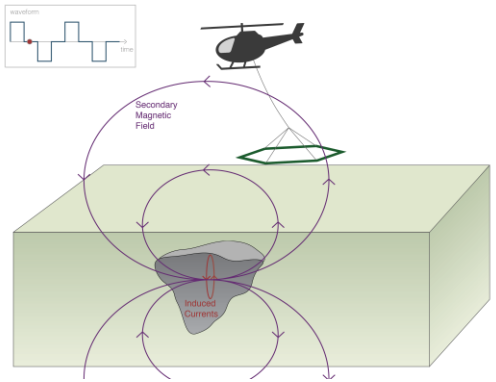
Magnetometer

- Measures:
  - Magnetic field
  - 3 components
- eg. 3-component fluxgate

$$\mathbf{b}(t)$$



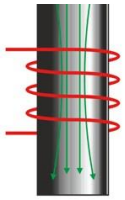
Fluxgate Squid



Coil

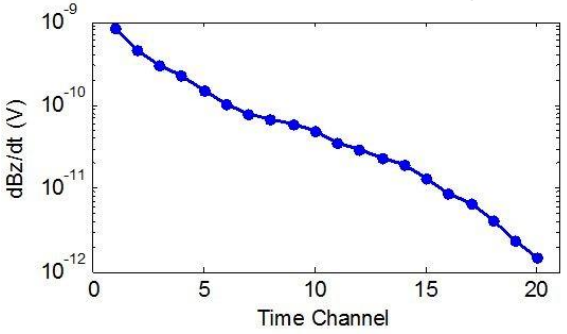
- Measures:
  - Voltage
  - Single component that depends on coil orientation
    - Coupling matters
- Airborne TDEM: measure db/dt

$$\frac{\partial b}{\partial t}$$



Coil

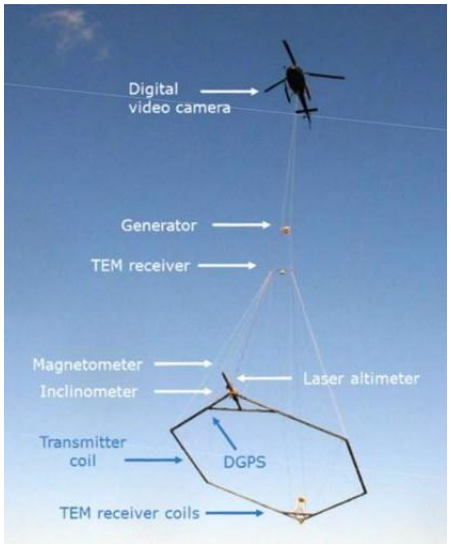
Measured decay



Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

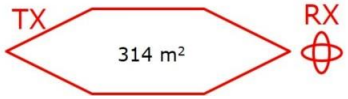
Some Airborne TDEM Systems

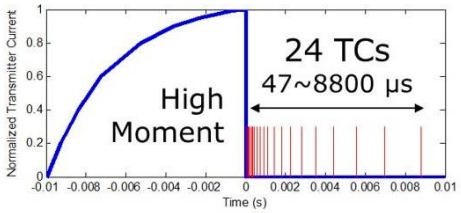
SkyTEM (2006)



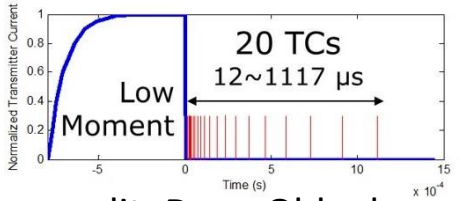
Area = 314 m^2

Peak dipole moment:
- HM: 113040 NIA
- LM: 12560 NIA



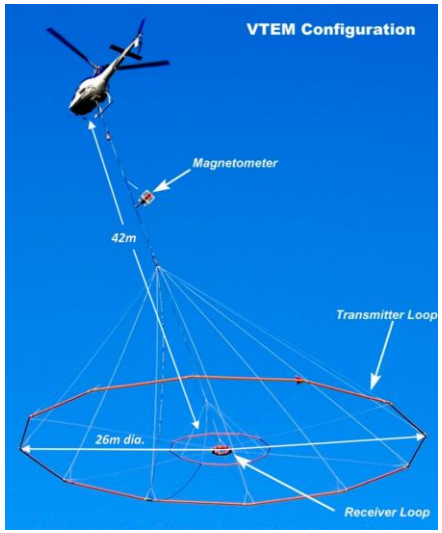


Peak current: 90 A
Turns: 4
On-time: 10 ms
Off-time: 10 ms



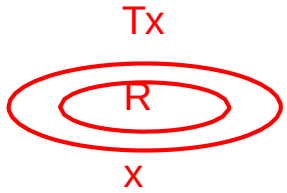
Peak current: 40 A
Turns: 1
On-time: 0.8 ms
Off-time: 1.45 ms

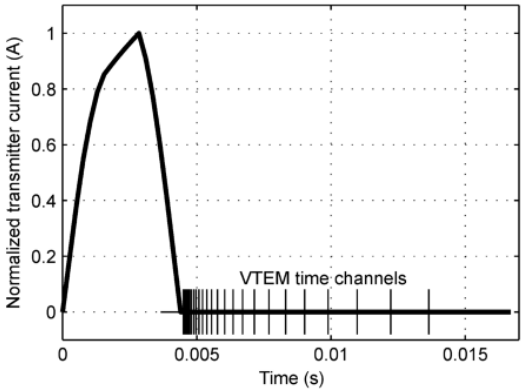
VTEM (2007)



Area = 535 m^2

Peak dipole moment:
- 503,100 NIA





Peak current: 235 A
Turns: 4
On-time: 4.5 ms
Off-time: 9.1 ms

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Optional materials on Airborne TDEM

- https://em.geosci.xyz/content/geophysical_surveys/airborne_tdem/index.html

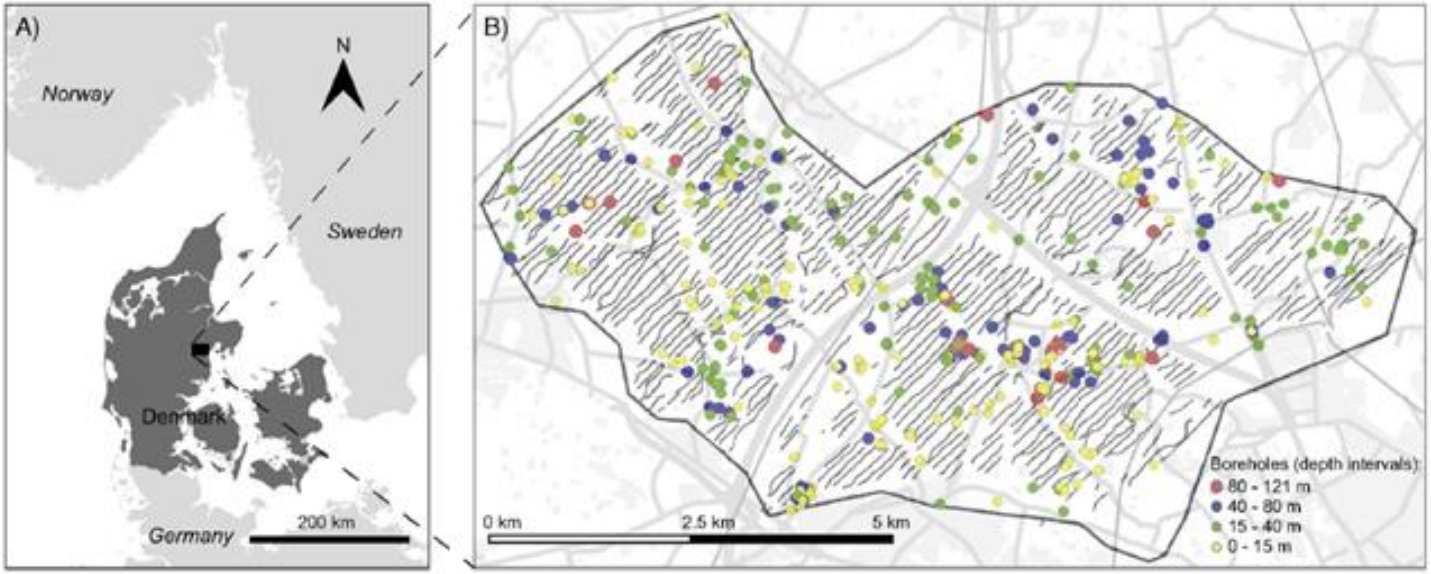
Case History: Kasted

Vilhelmsen et al. (2016)

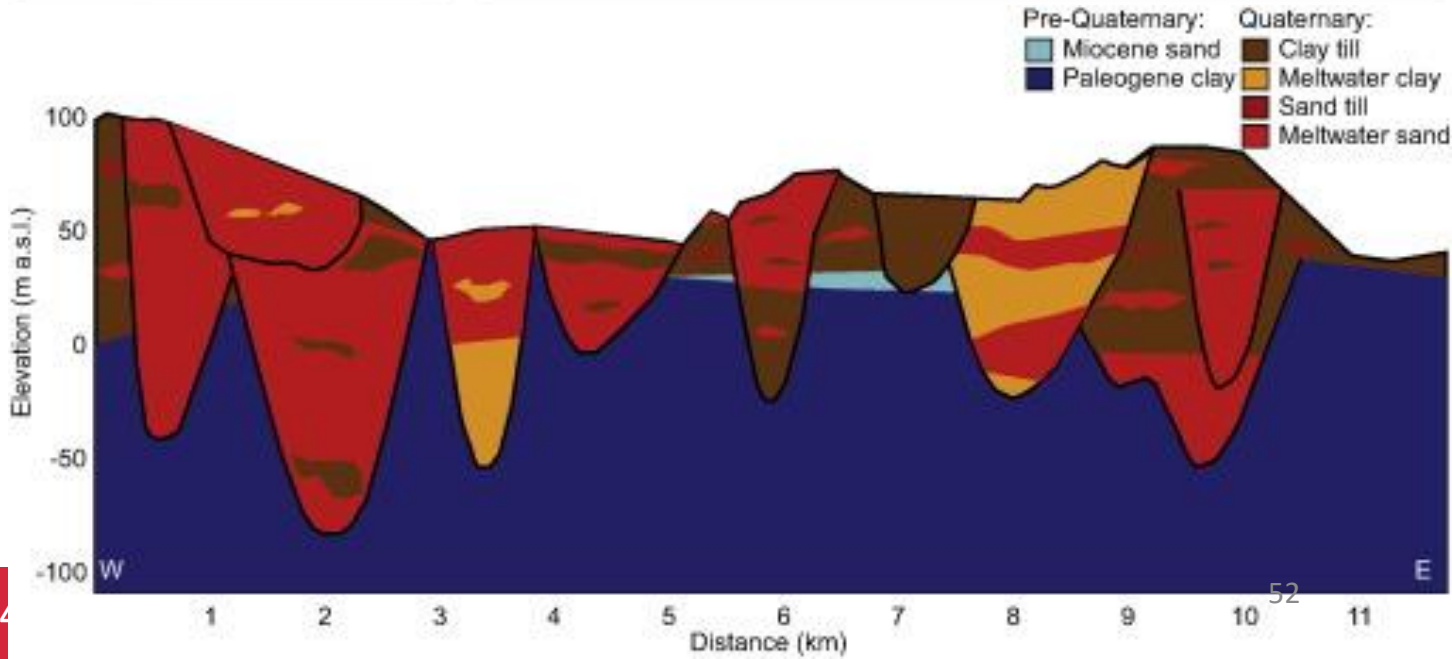
Setup

A) Survey Area: Kasted, Demark

B) Borehole locations

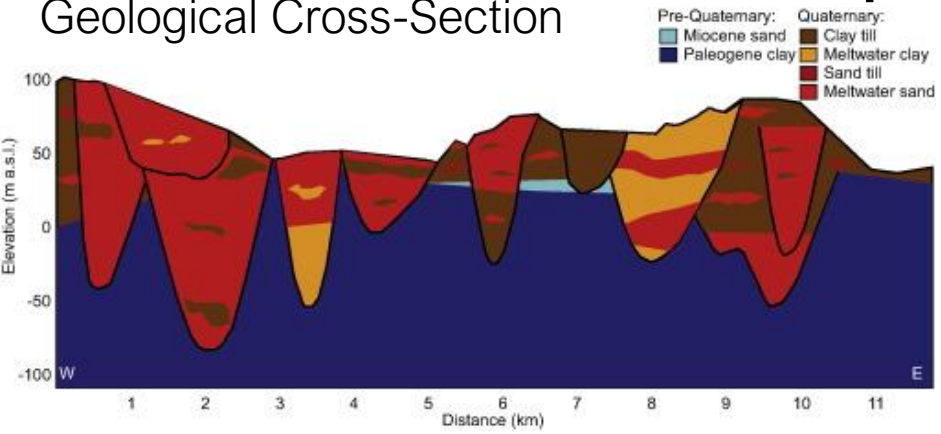


Local Geology: W-E cross-section



Properties

Geological Cross-Section

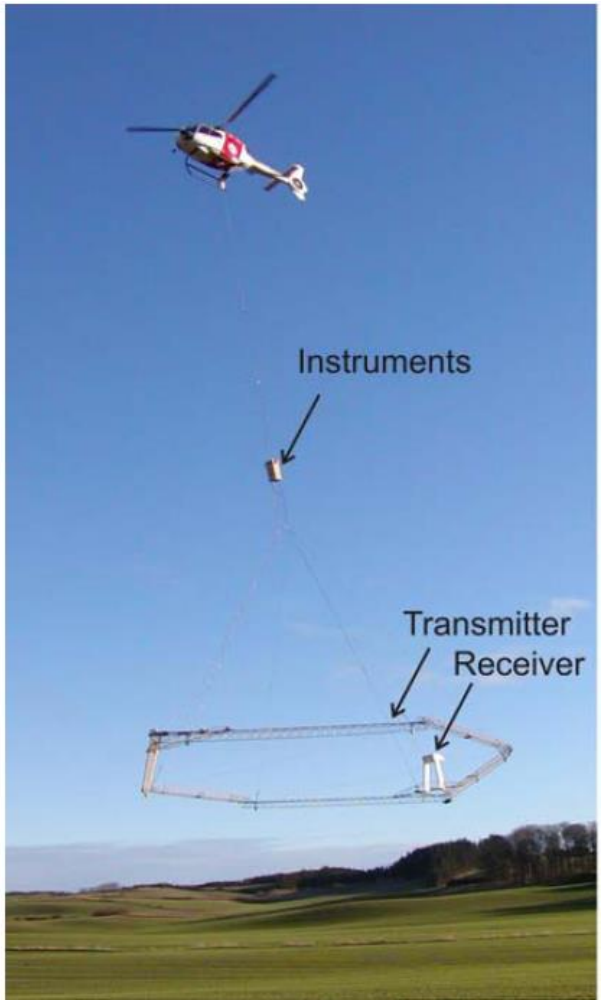


Geological Units	Resistivity (Ωm)
Palaeogene Clay	1-10
Clay Till	25-60
Sand Till	>50
Meltwater Sand and Gravel	>60
Glaciolacustrine Clay	10-40
Miocene Silt and Sand	>40
Miocene Clay	10-40
Sand	>40
Clay	1-60

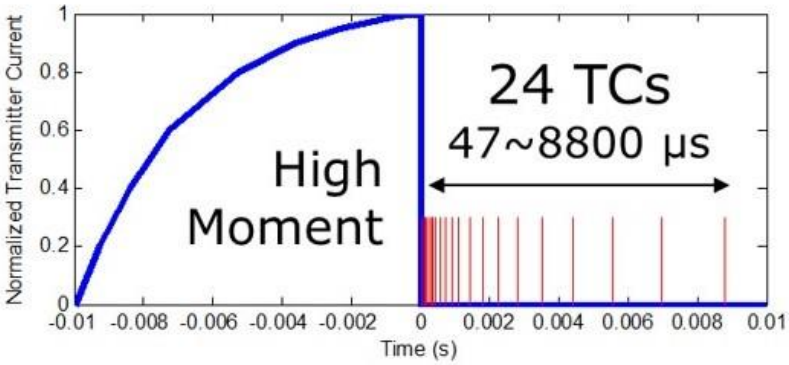
- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40 Ωm)
- Water-bearing sands and gravels are more resistive (>40 Ωm)

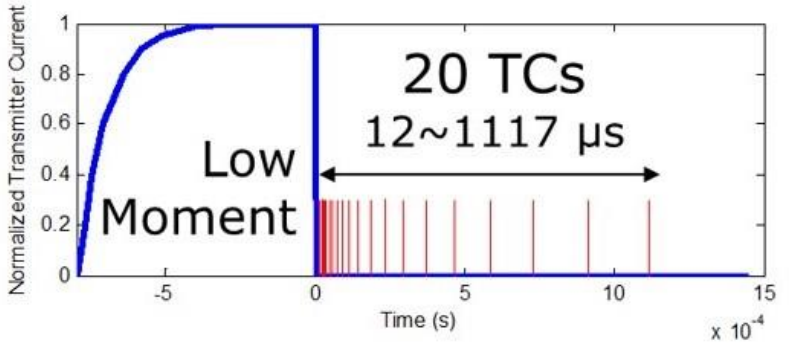
Survey

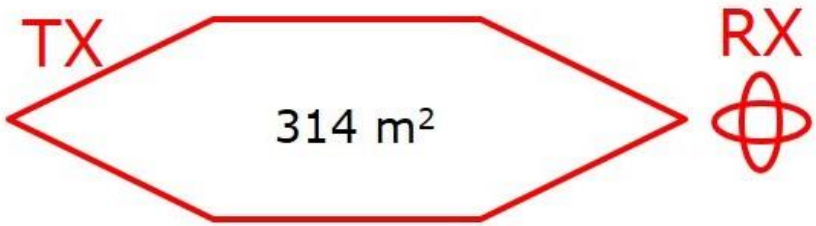
SkyTEM System



System Configuration



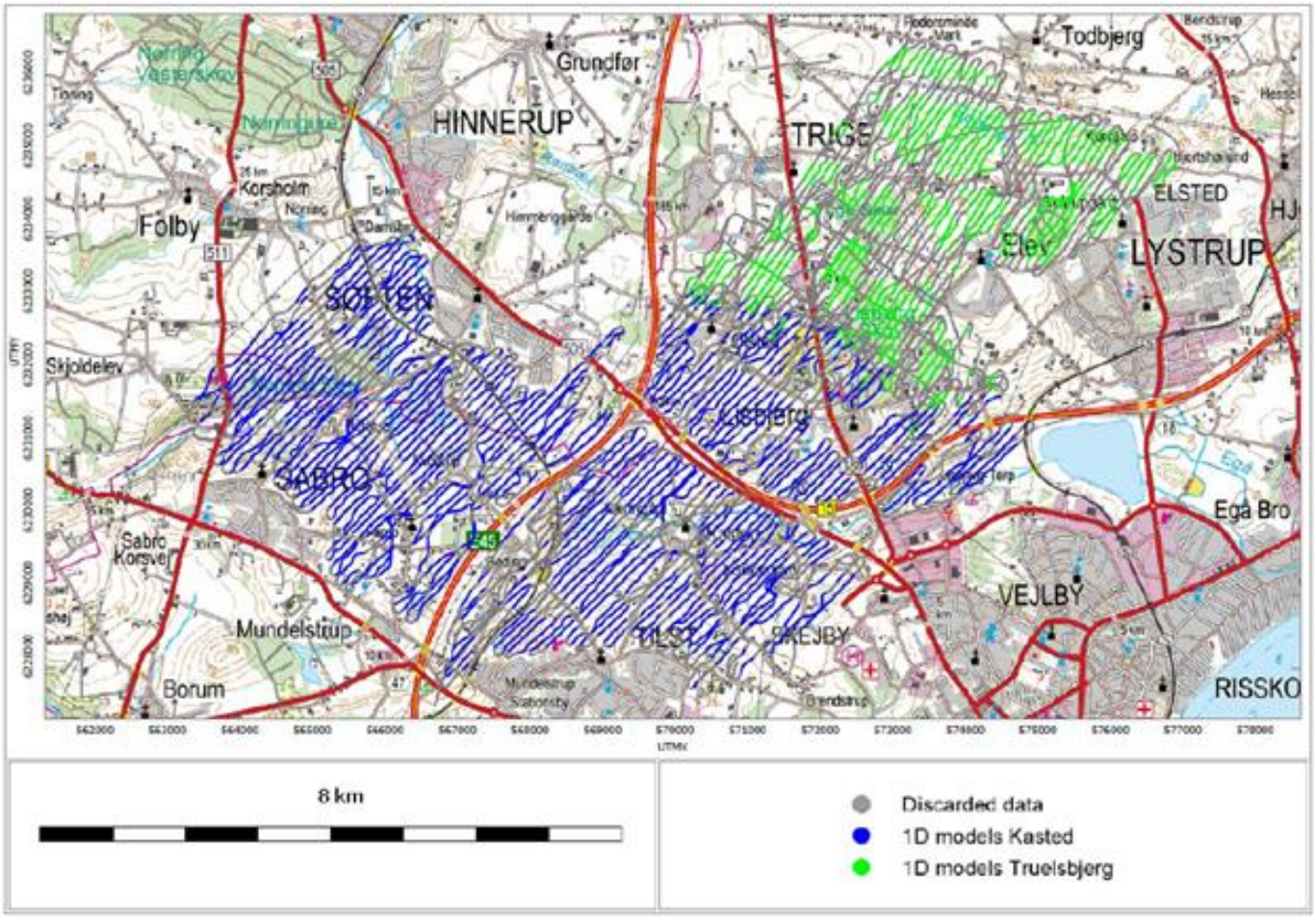




- Low moment (LM) used to image near surface structures
- High moment (HM) used to image deeper structures

Data

Blue: data used for Kasted study

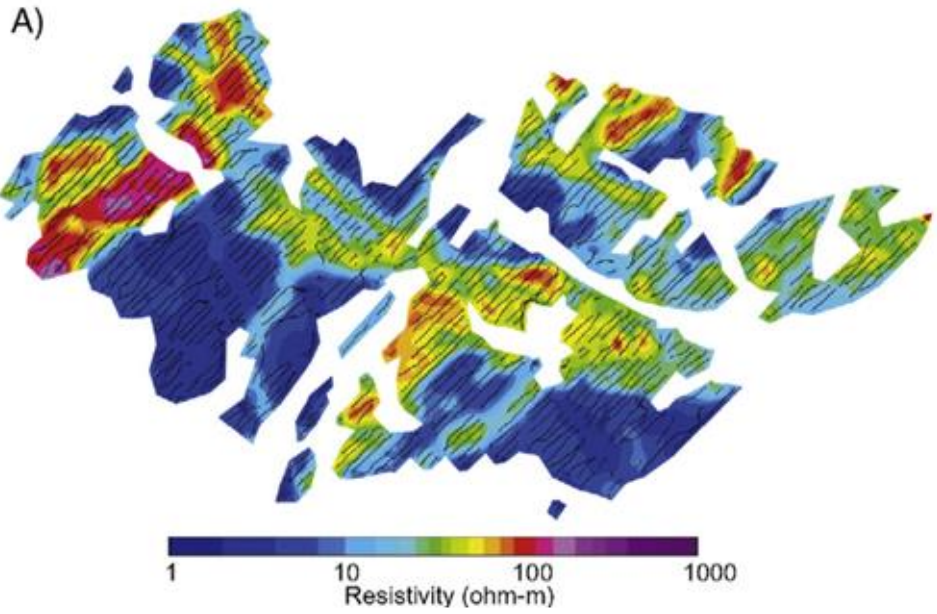


- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

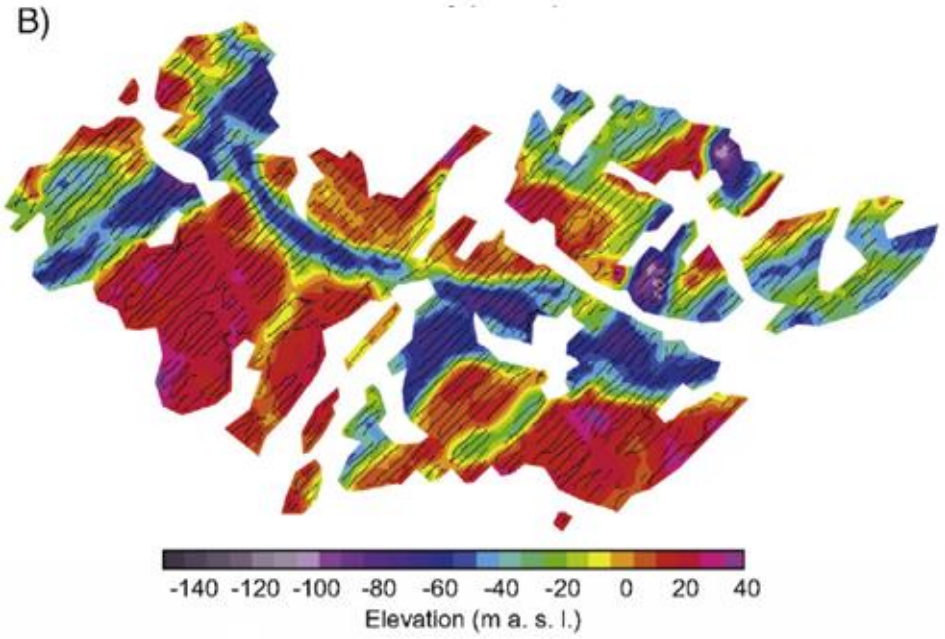
Processing (inversion)

- Spatially constrained 1D inversion → quasi-3D approach
- 9,500 soundings were inverted using 25 layers

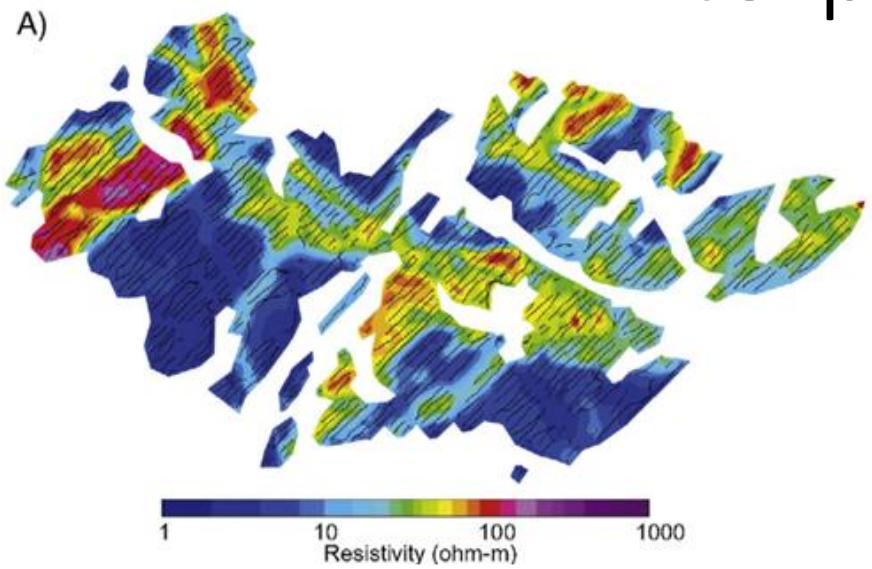
Depth slice 5 m above sea-level

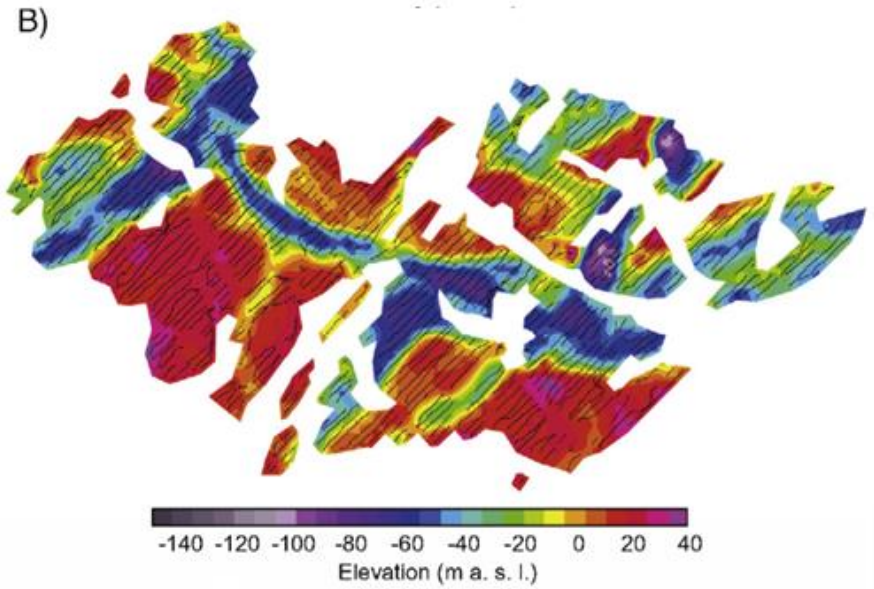


Approximate depth to the top of Paleogene clay layer

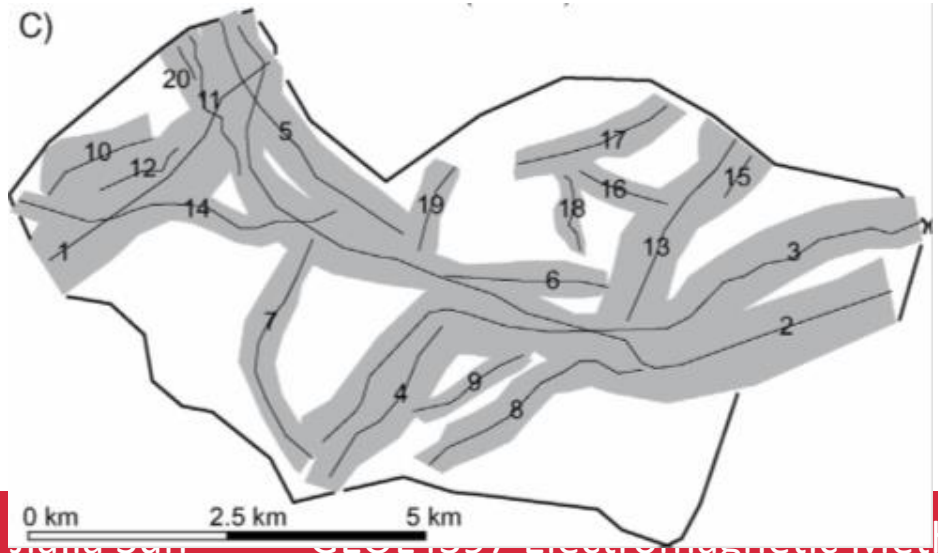


Interpretation



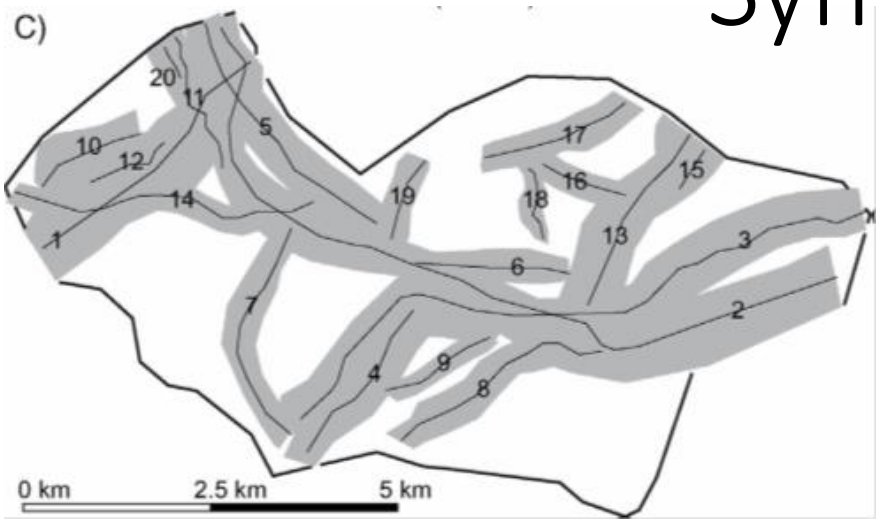


Delineation of valley structures

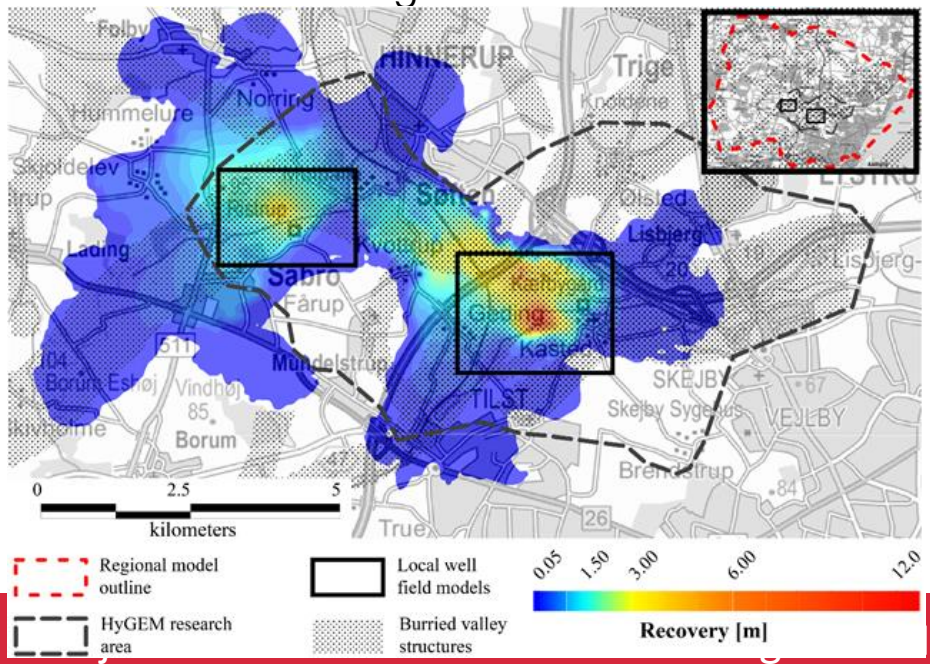


- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

Synthesis



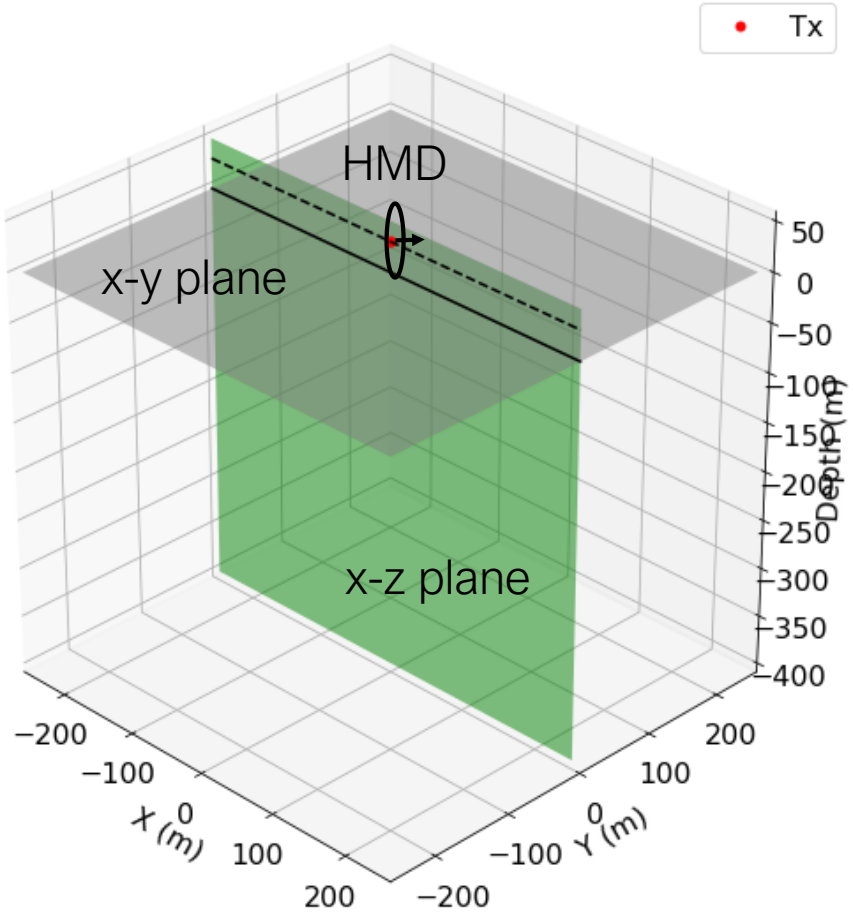
MODFLOW-USG groundwater model



- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool
- Extracted water from 2 wells.
- Drawdown between the two wells correlated with the resistive valley structures

Optional materials on horizontal magnetic dipole

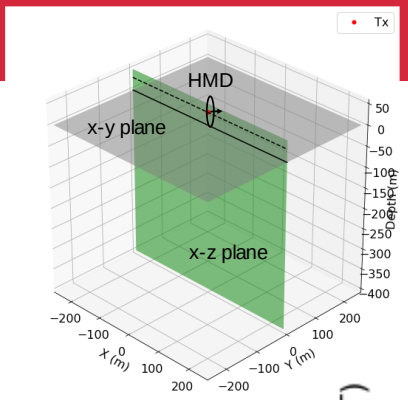
Horizontal Magnetic Dipole (HMD)



- Same physical principles as VMD, but different source geometry
- Focus on magnetic field and currents
- Different coupling for conductive targets

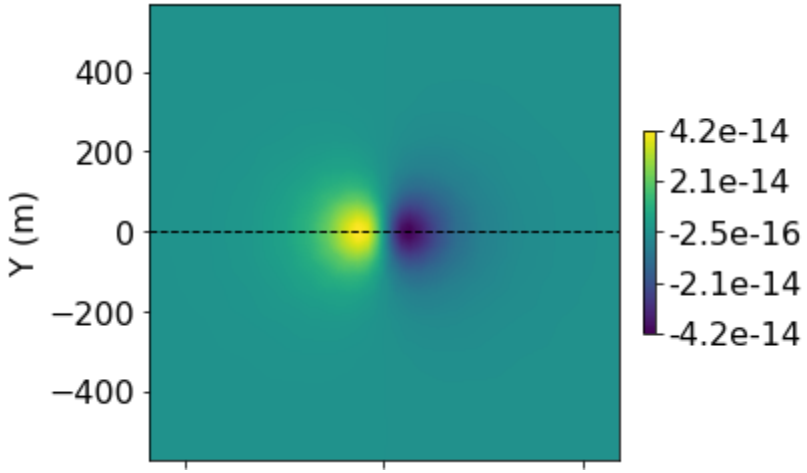
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

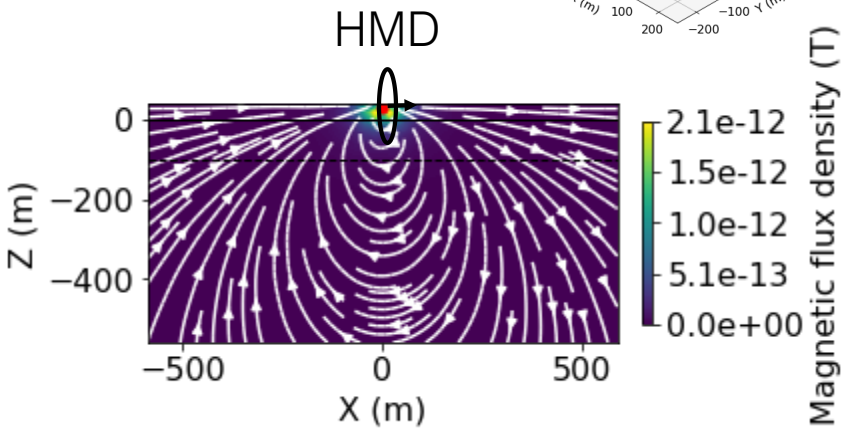
Magnetic field



Magnetic field

b_z component

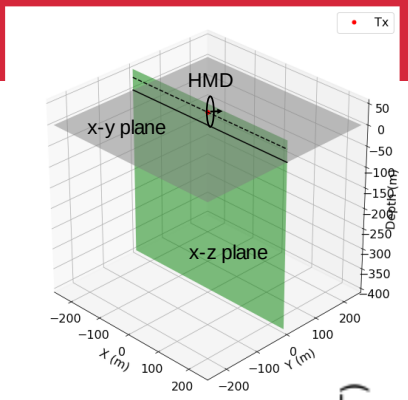




What currents can generate these magnetic fields?

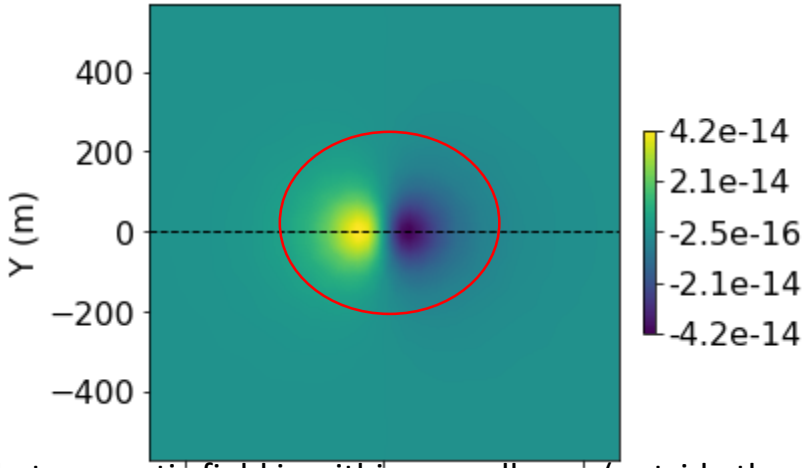
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Magnetic field



Magnetic field

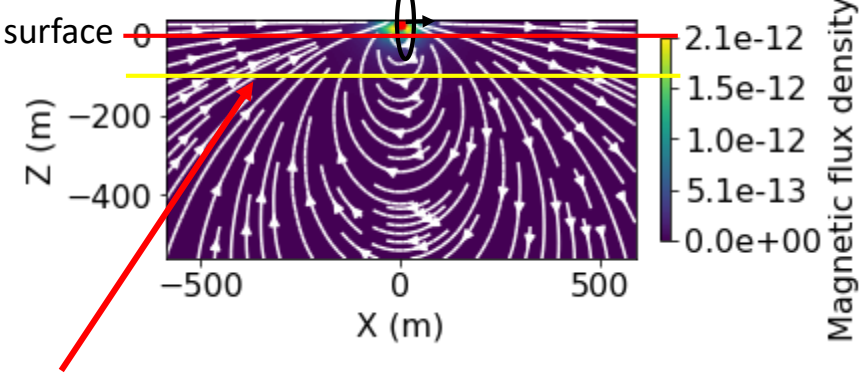
b_z component



Note that magnetic field is within a small area (outside the circle, B field is very very small). Therefore, an infinitely long wire carrying current going into the page is not good to reproduce the B field in the figure, because the B field from an infinitely long wire is not localized within a small region. Instead, a current loop (or loops) is better at reproducing such B field.

HMD

Note that HMD is above the surface

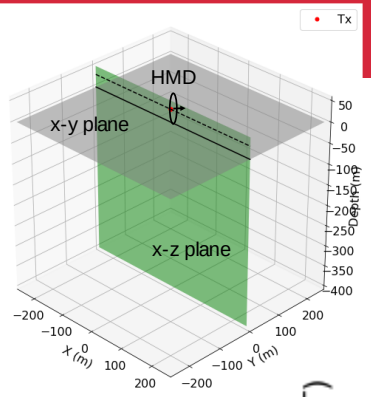


We can also consider this as the surface. Then the height of HMD will be the current height plus the thickness of the layer (bounded by the surface of the Earth and the yellow line)

What currents can generate these magnetic fields?

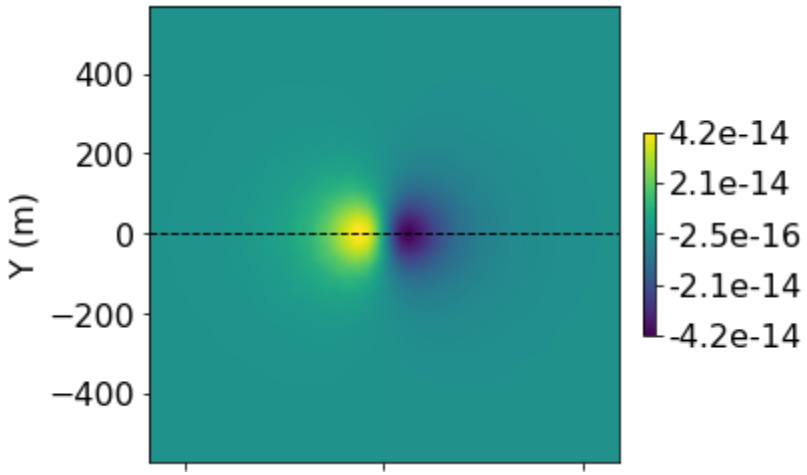
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Magnetic field and Current

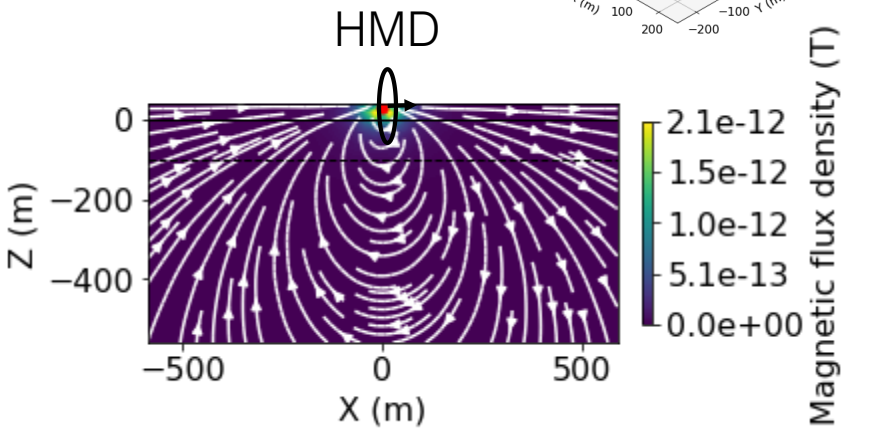


Magnetic field

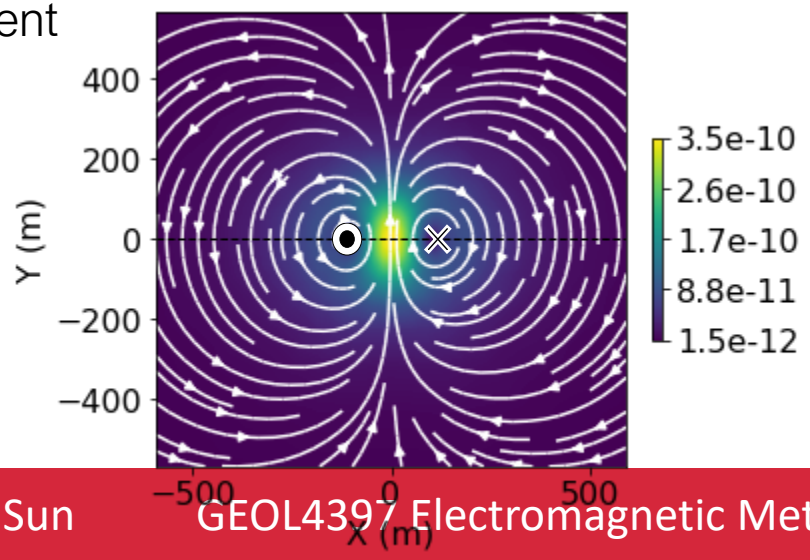
b_z component



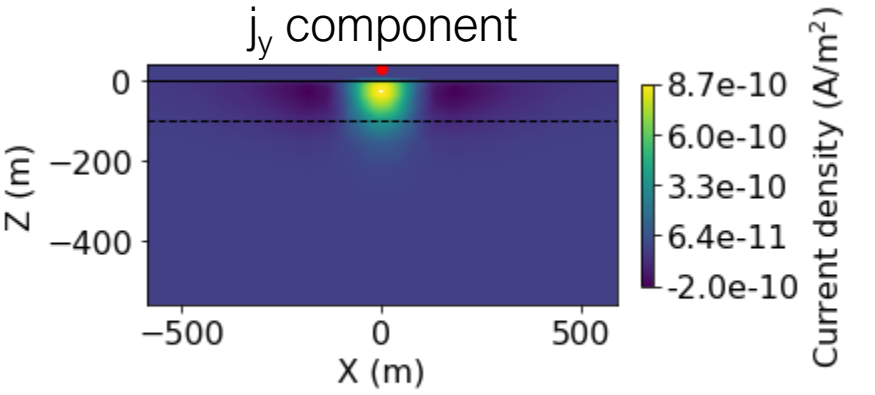
HMD



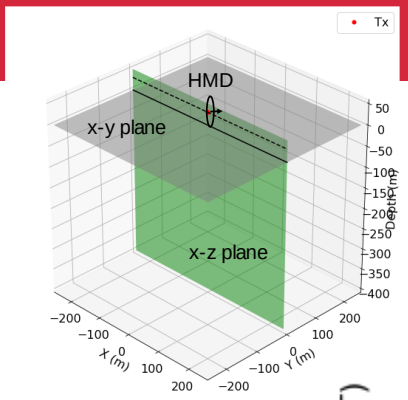
Current



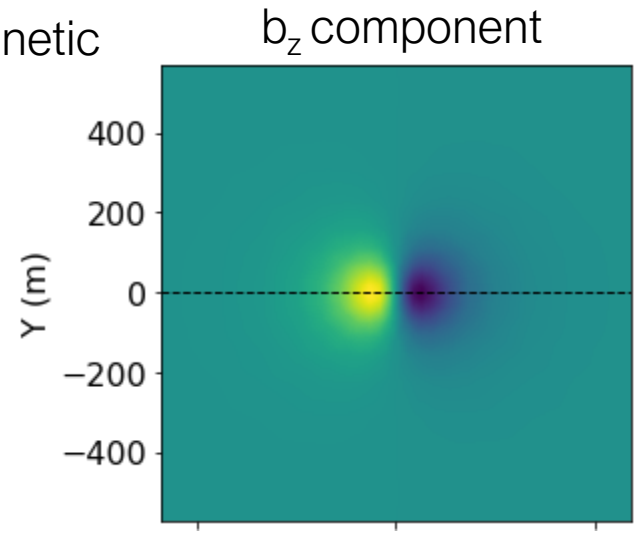
j_y component

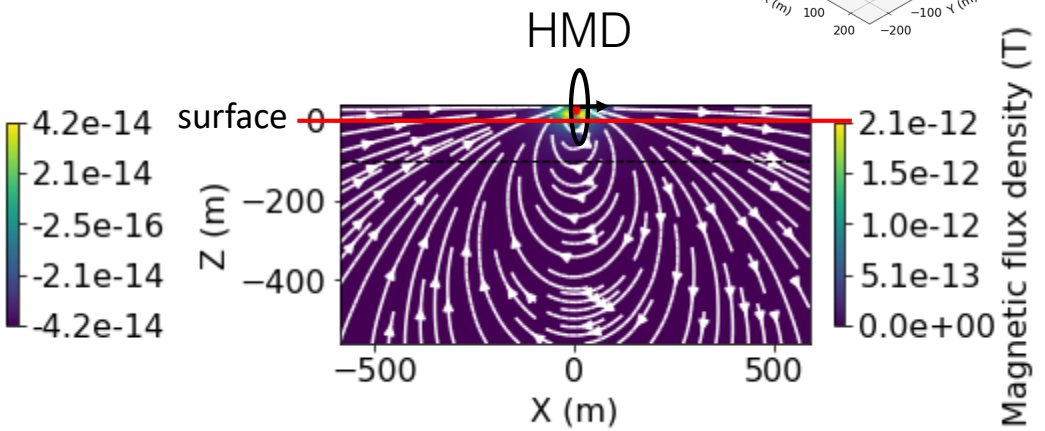


Magnetic field and Current



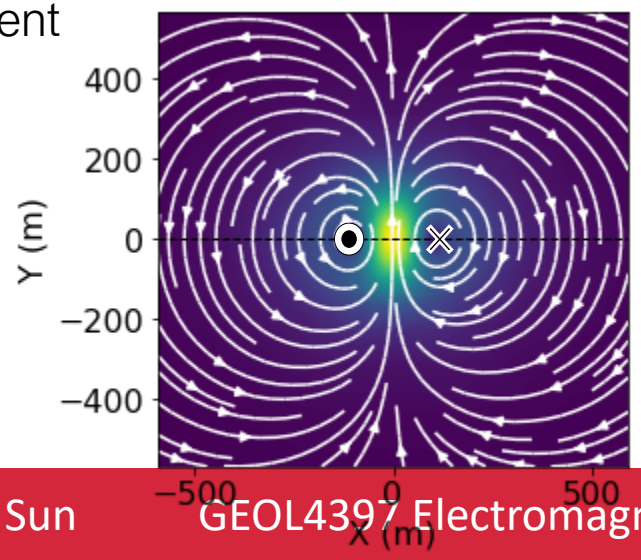
Magnetic field

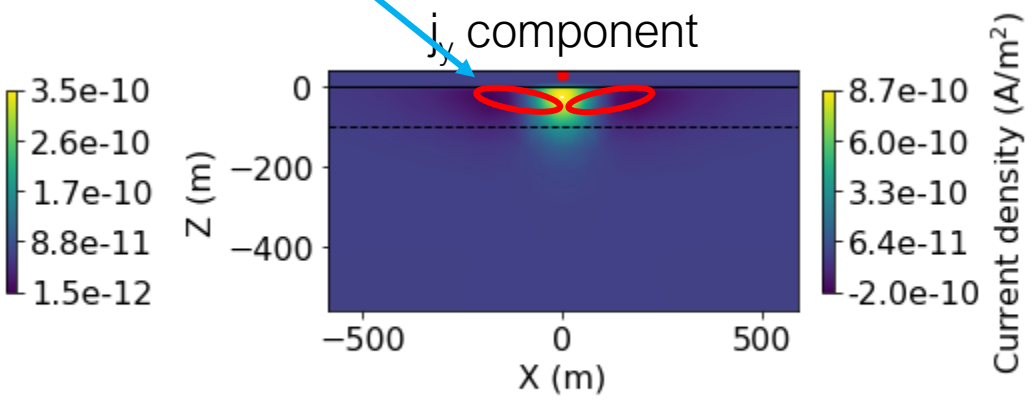




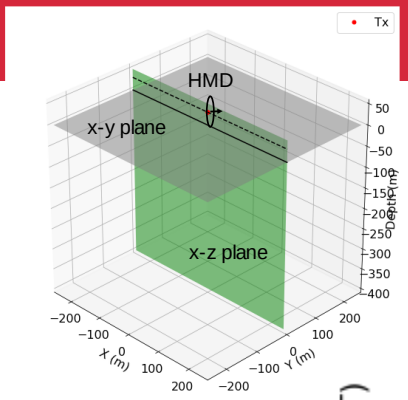
We can consider the induced currents as those from two tilted current loops. The are tilted because the directions of the magnetic field lines at the surface are not vertical, but tilted.

Current

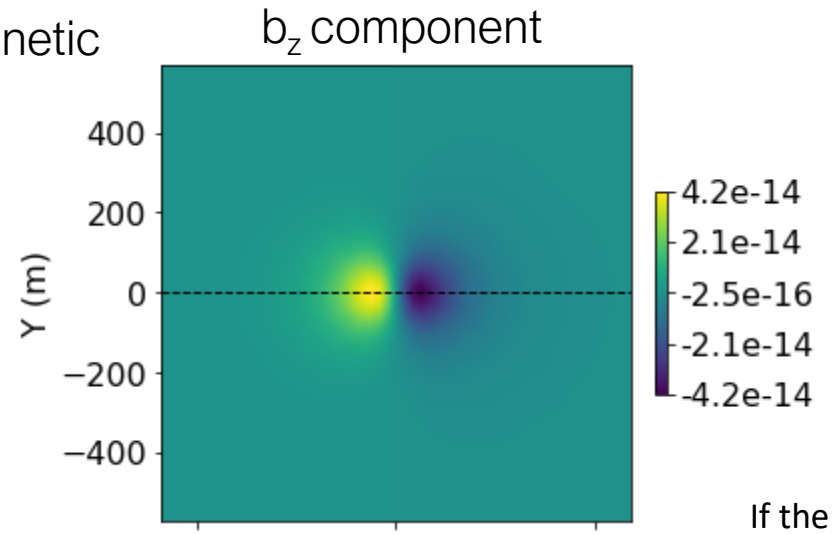


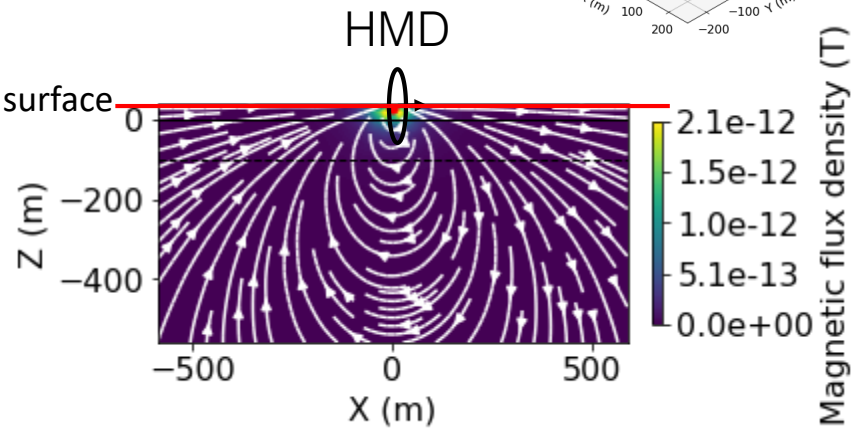


Magnetic field and Current

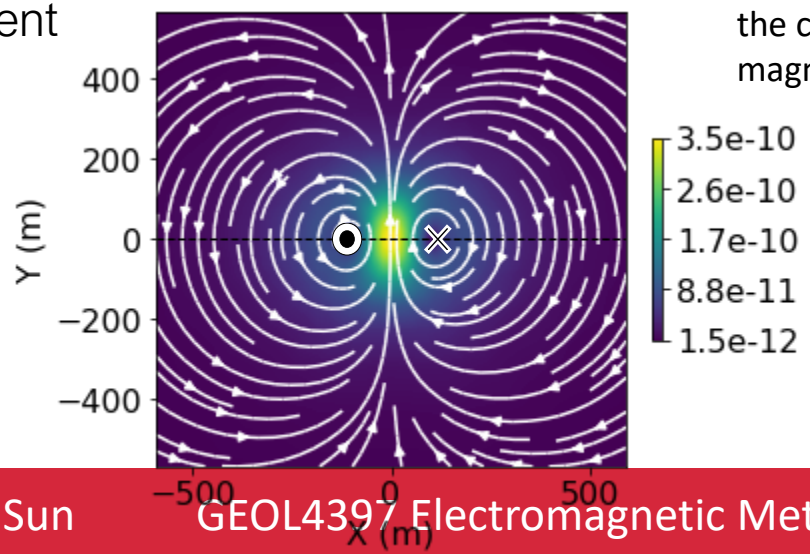


Magnetic field

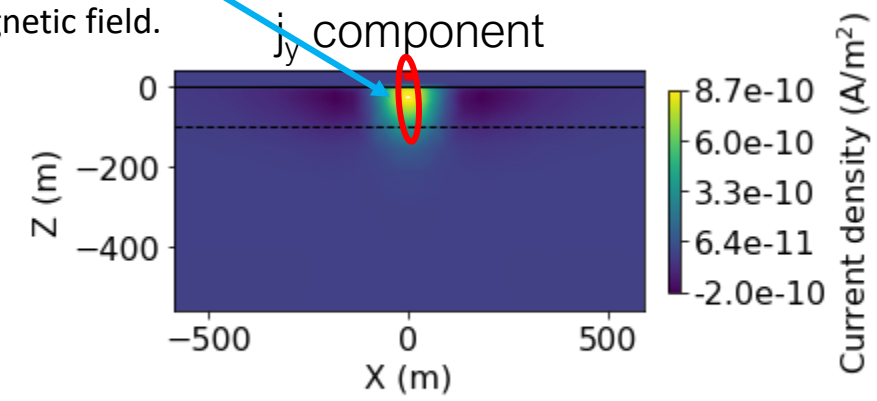




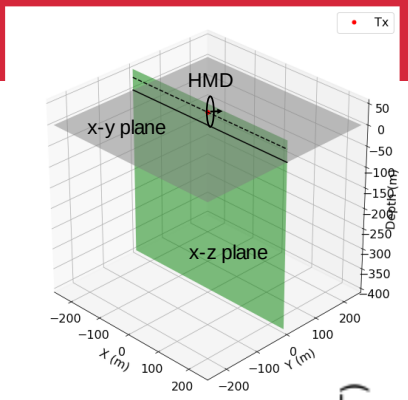
Current



If the HMD is located right on the surface. Then the directions of the magnetic field line on the surface are horizontal. Then the current loop needs to be vertical in order to reproduce the magnetic field.

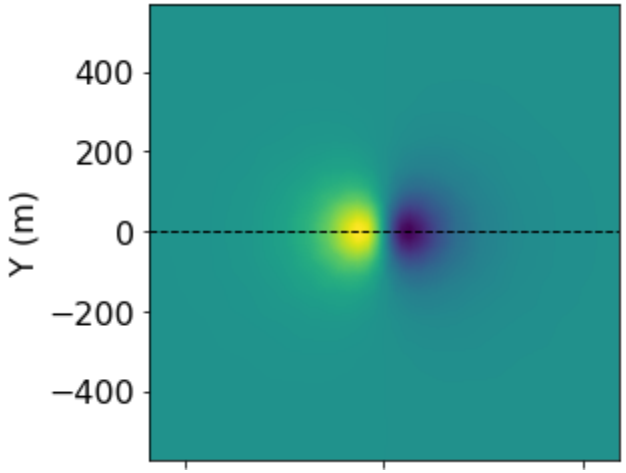


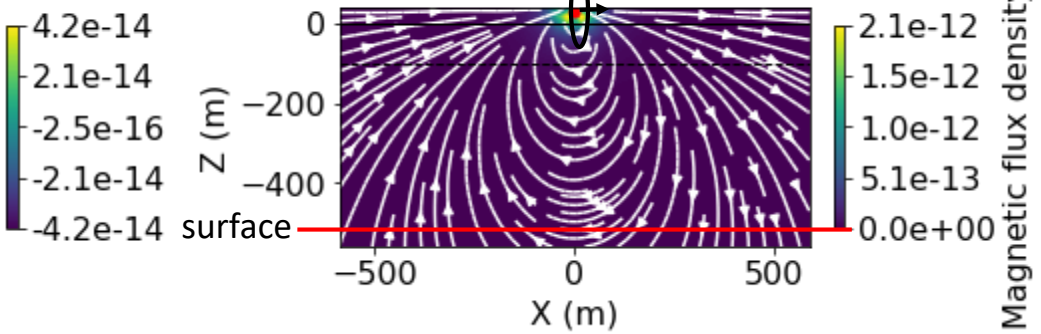
Magnetic field and Current



Magnetic field

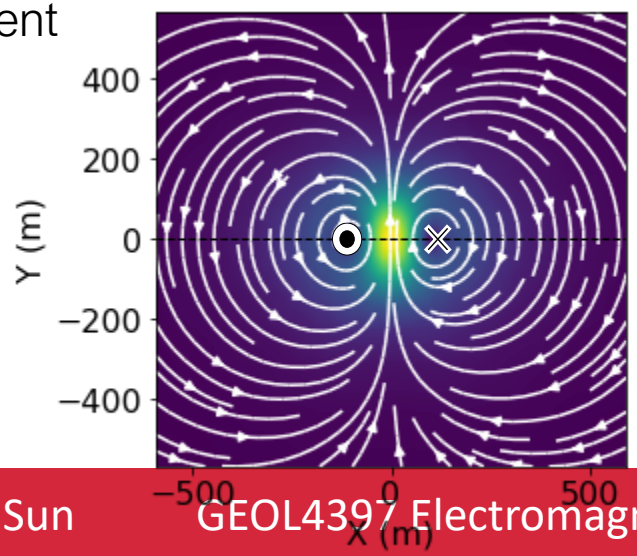
b_z component



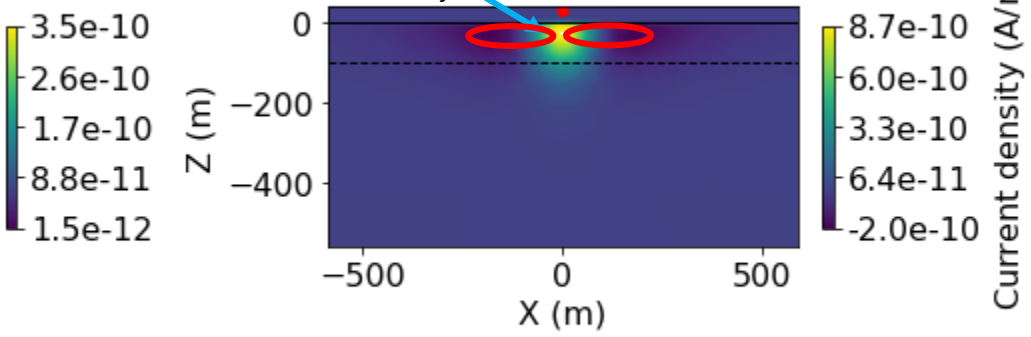


If the surface is at the location of the red line. Then the directions of the magnetic field line on the surface are vertical on the far field. Then the current loop needs to be horizontal in order to reproduce the magnetic field.

Current

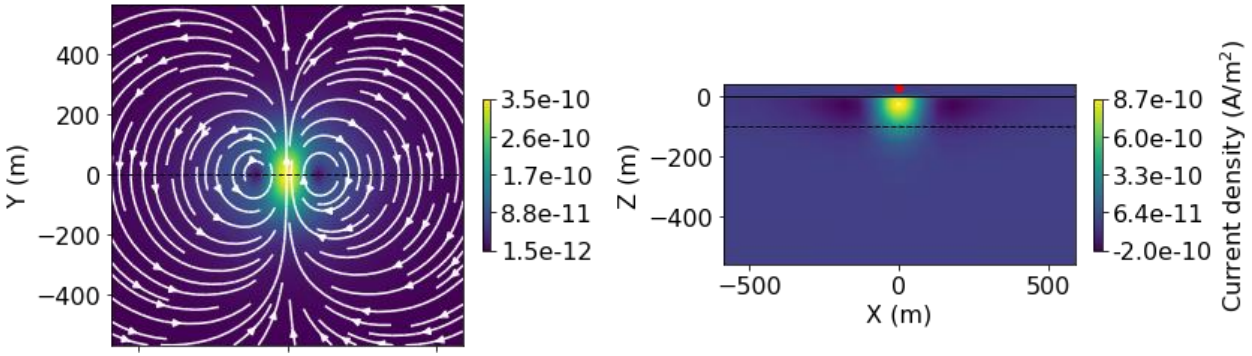


j_y component



Current in time

t=0.03ms

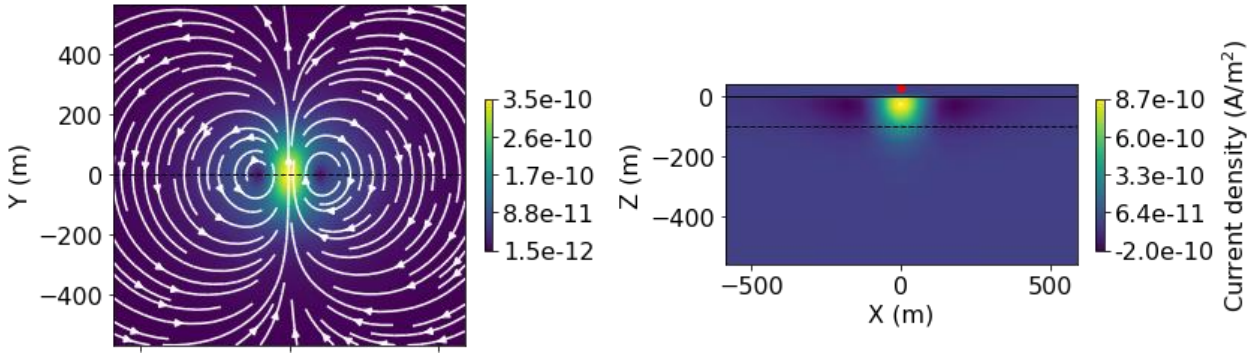


t=0.13ms

t=0.63ms

Current in time

t=0.03ms



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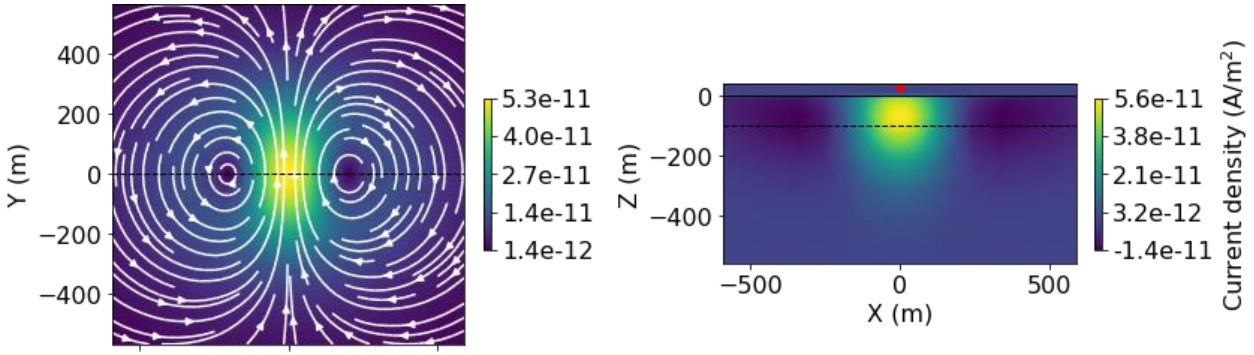
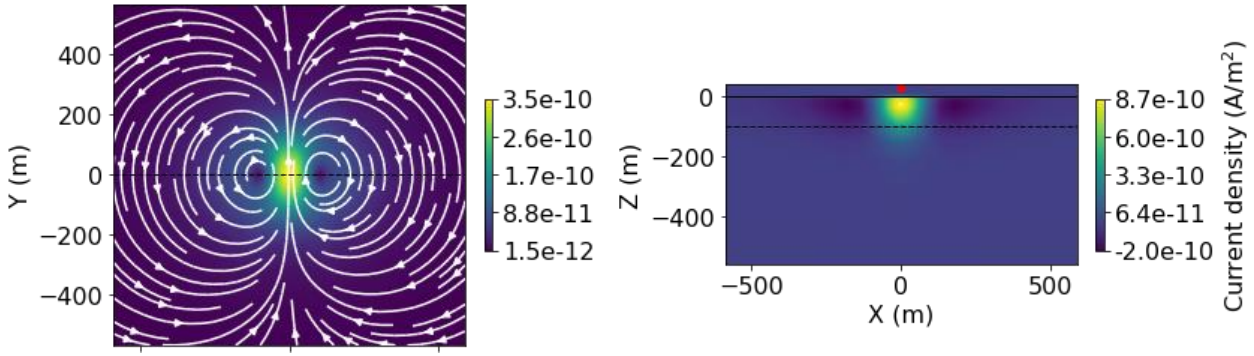


t=0.63ms

Current in time

t=0.03ms



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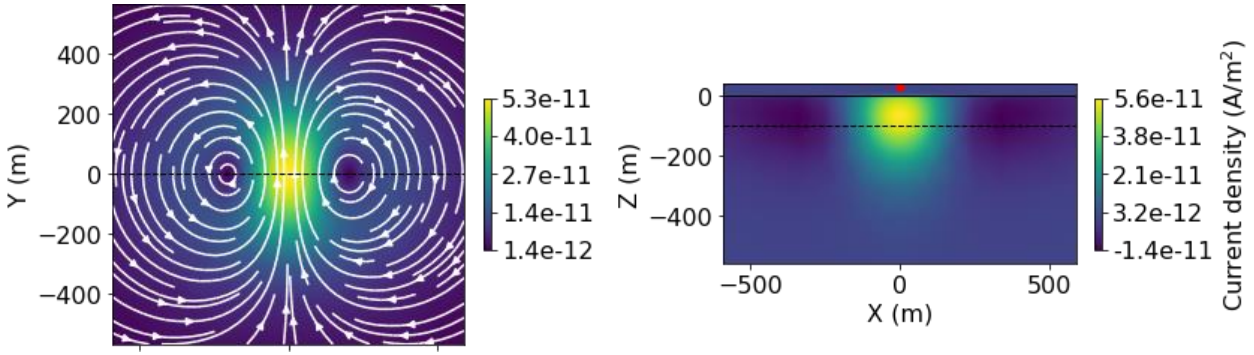

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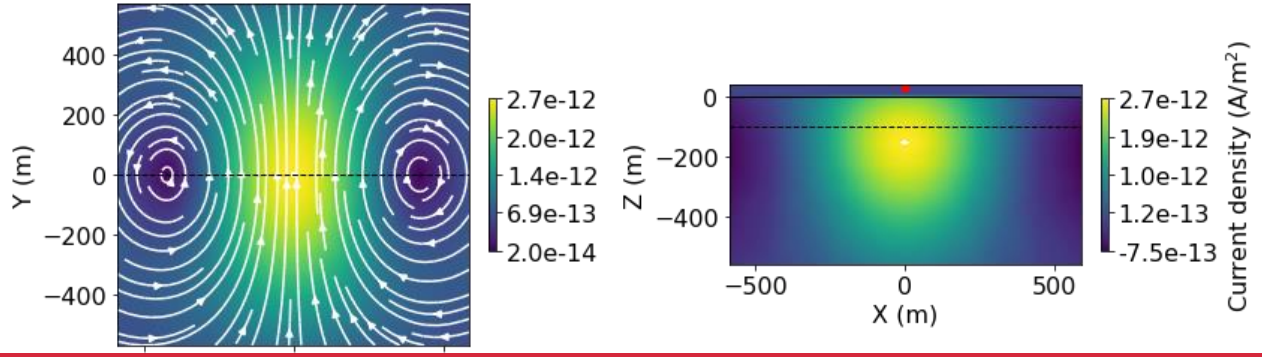
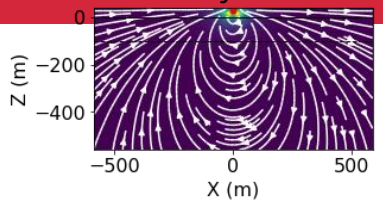
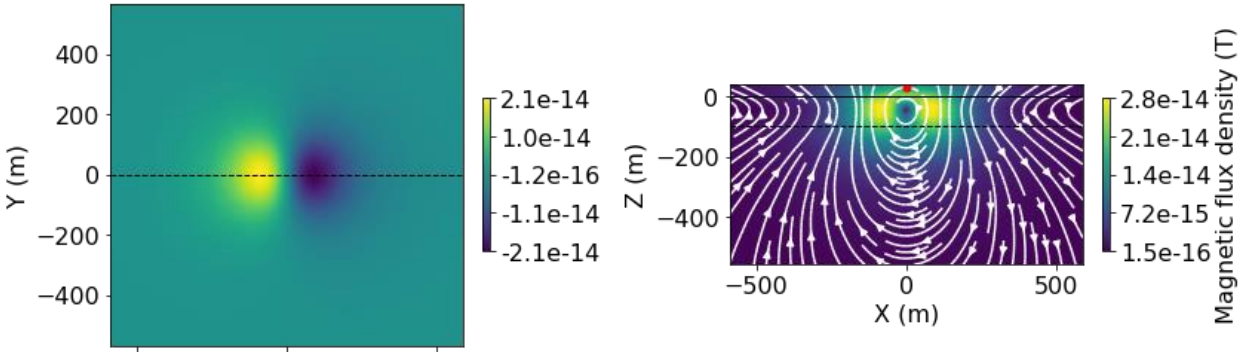


Magnetic field in time

Primary field

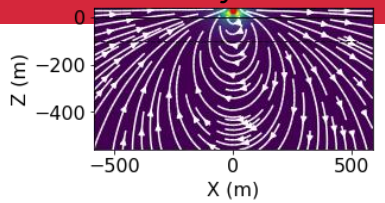


t=0.03ms

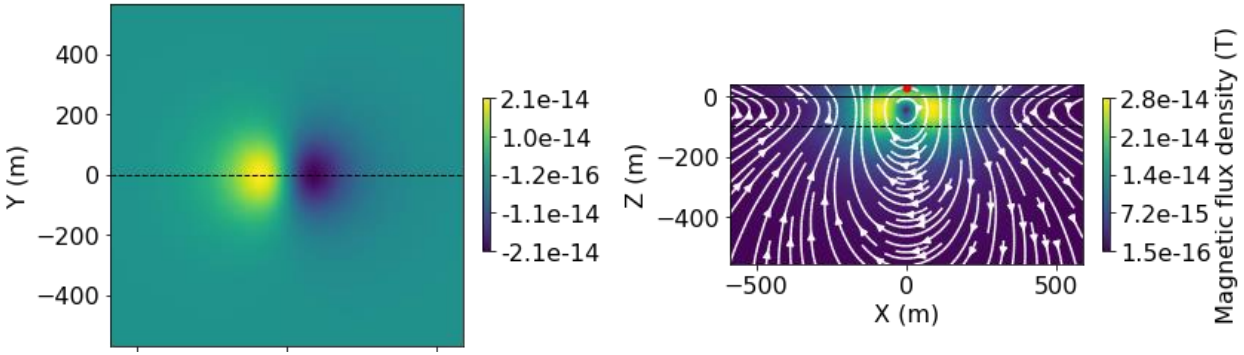


Magnetic field in time

Primary field



t=0.03ms



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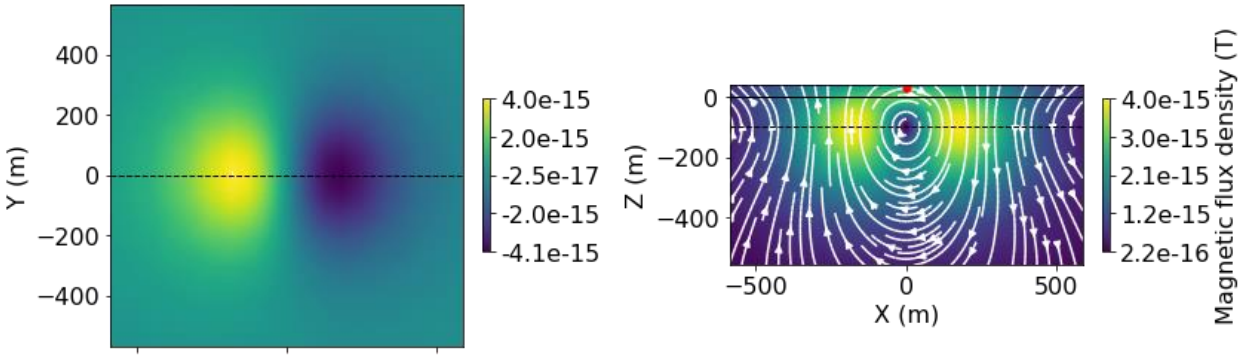
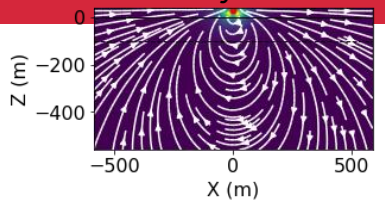


Magnetic field in time

Primary field



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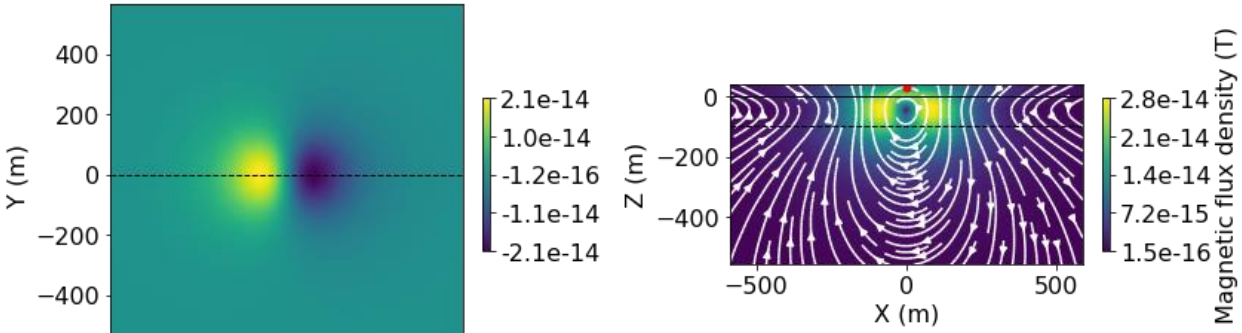

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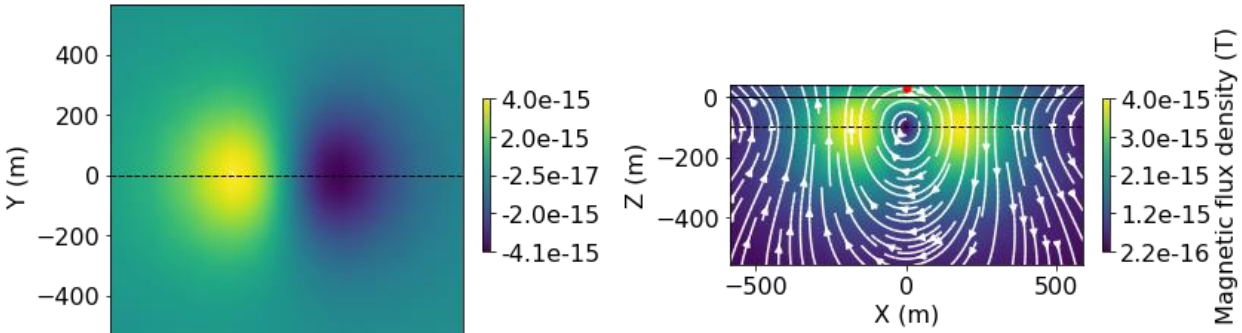

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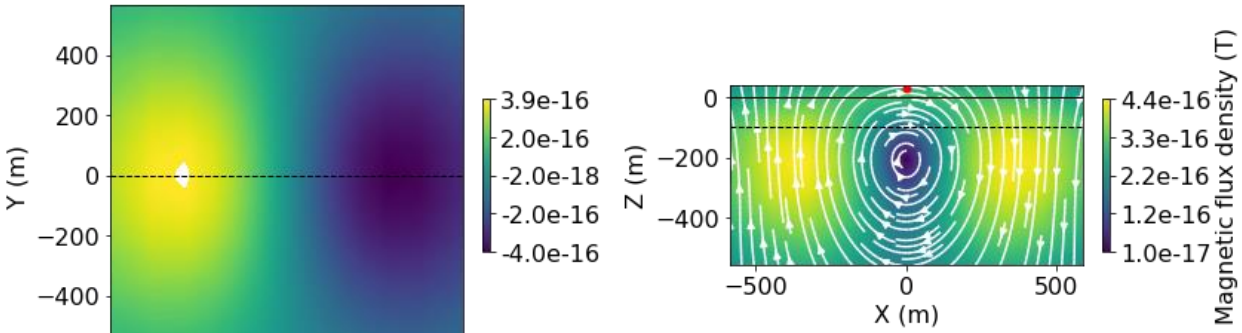
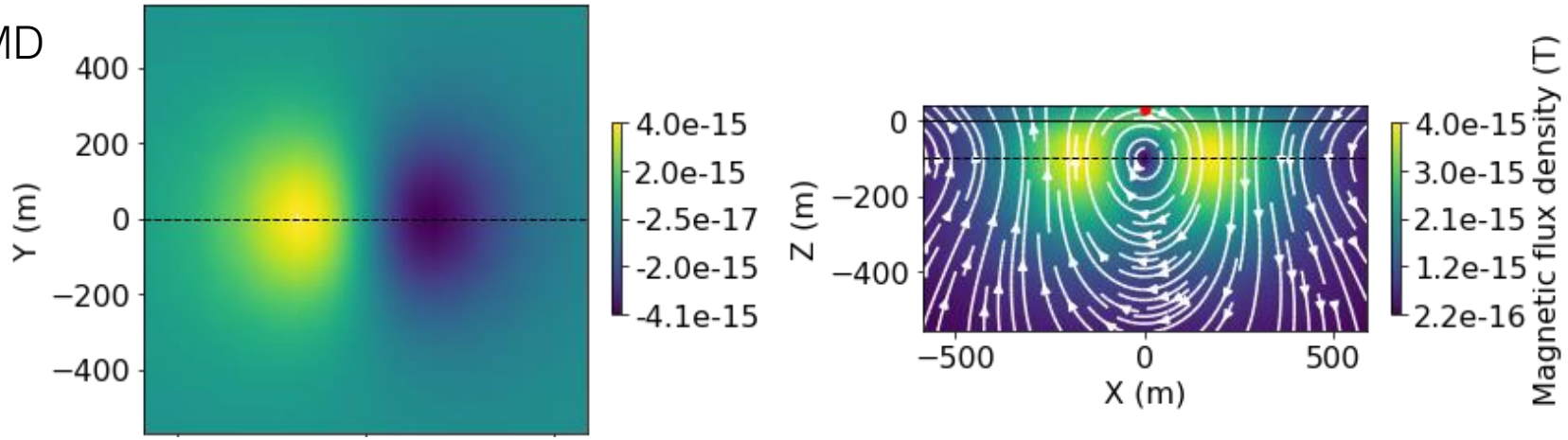


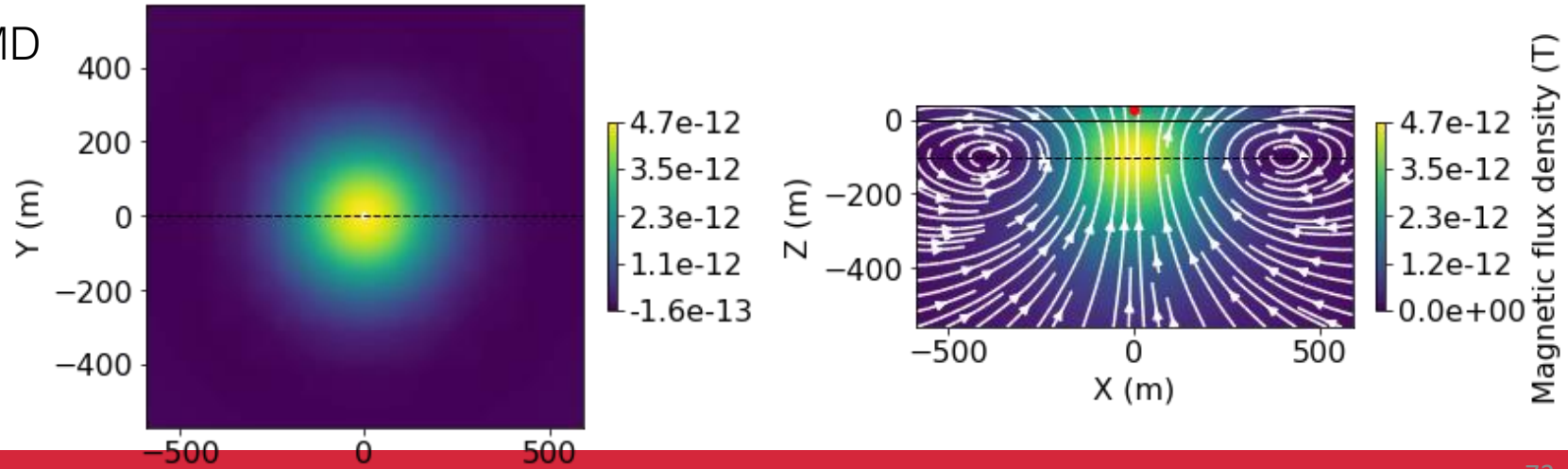
How different from VMD?

Magnetic field at 0.63 ms

HMD



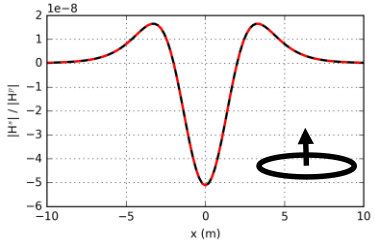
VMD



Coupling to a vertical plate

- Assume coincident loop case (Tx and Rx are coincident)
  - Both VMD and HMD
- Consider a profile line data (multiple time channels)
- Imagine how profile response will look like?

Recall three loops



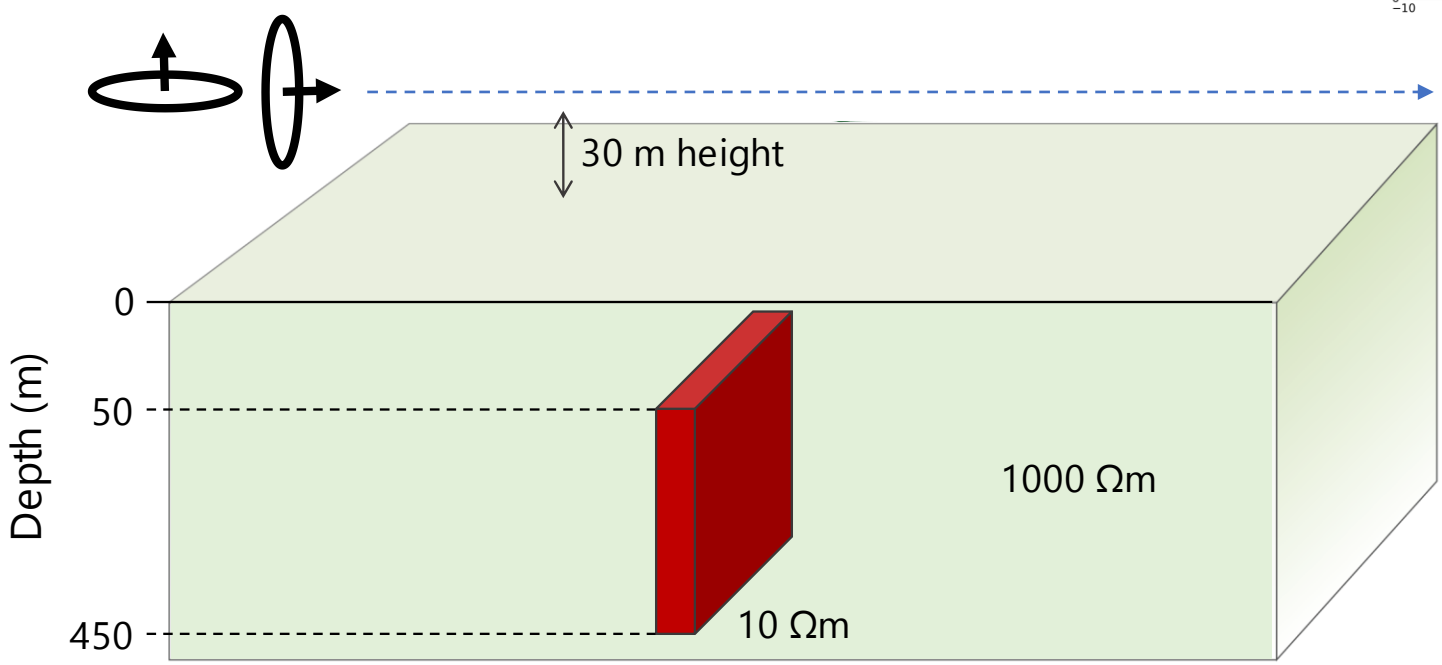
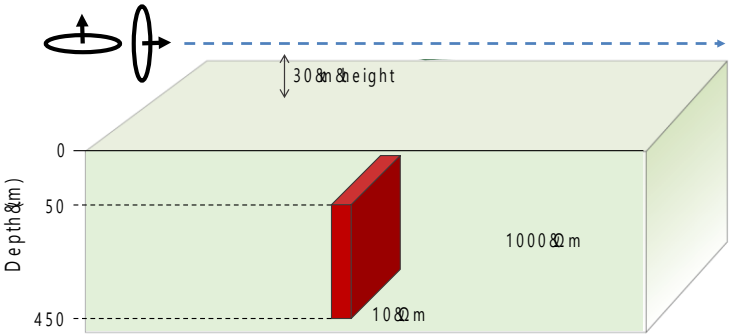
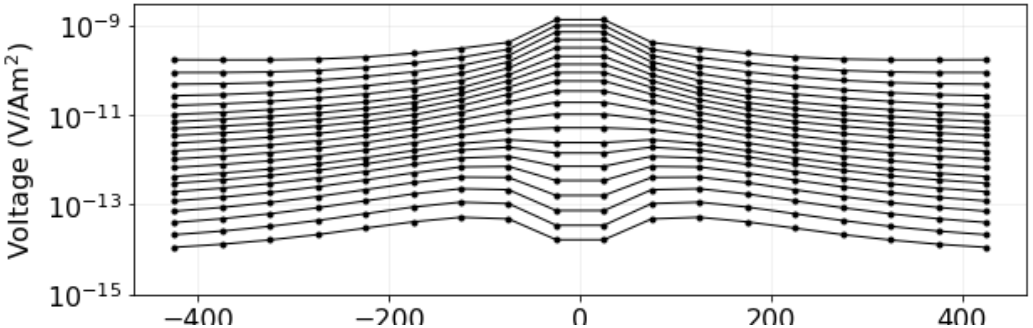


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

VMD vs. HMD: profile line data





Recall three loops

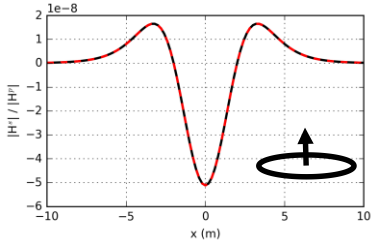
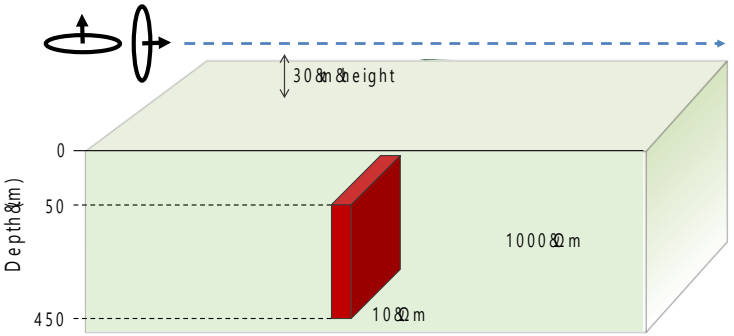
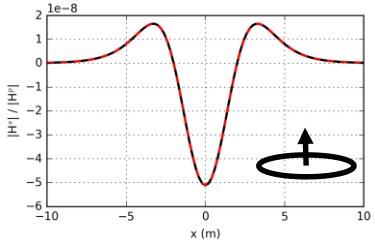


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

VMD vs. HMD: profile line data



Recall three loops



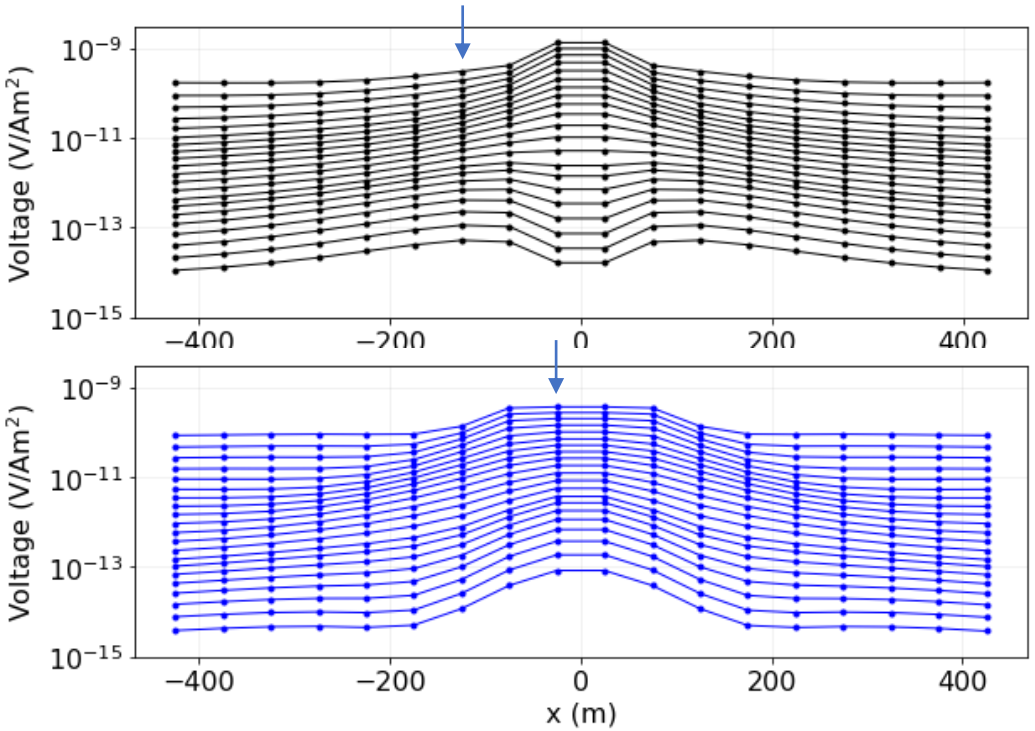
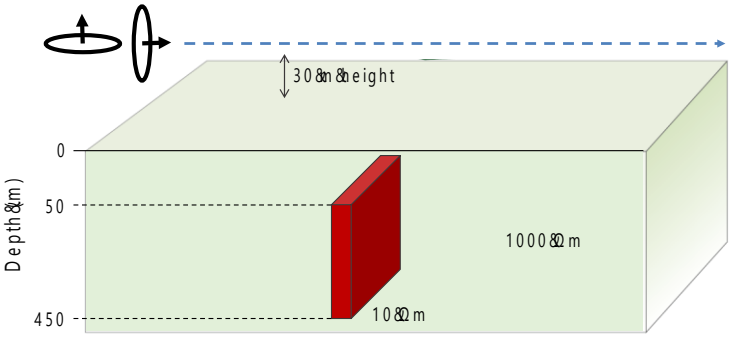
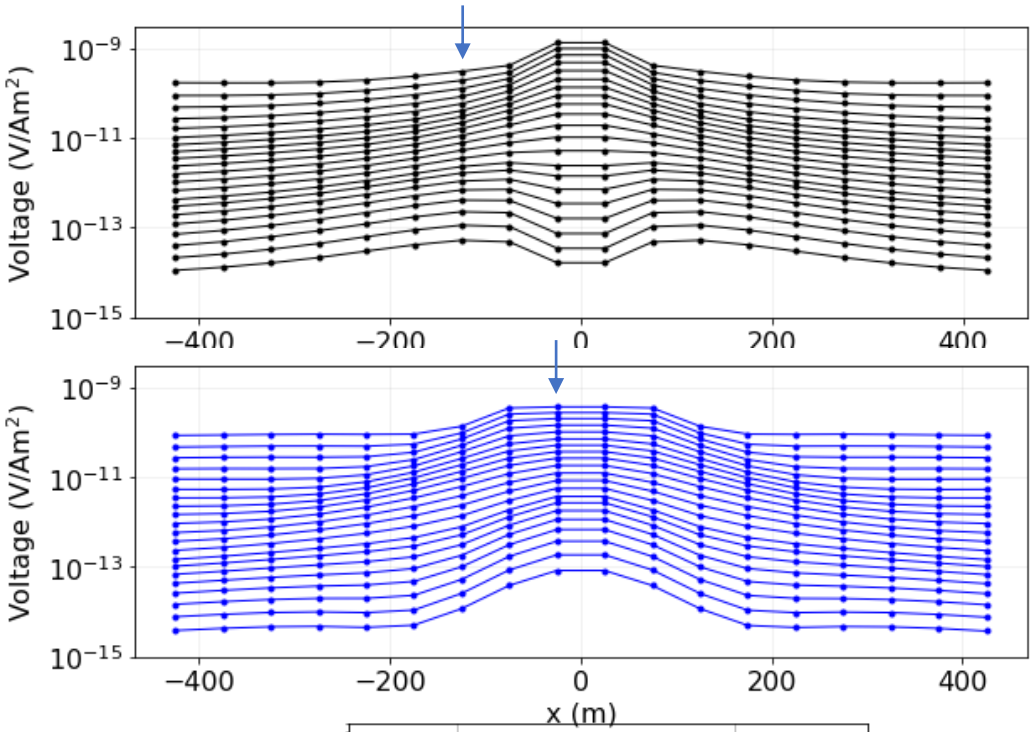
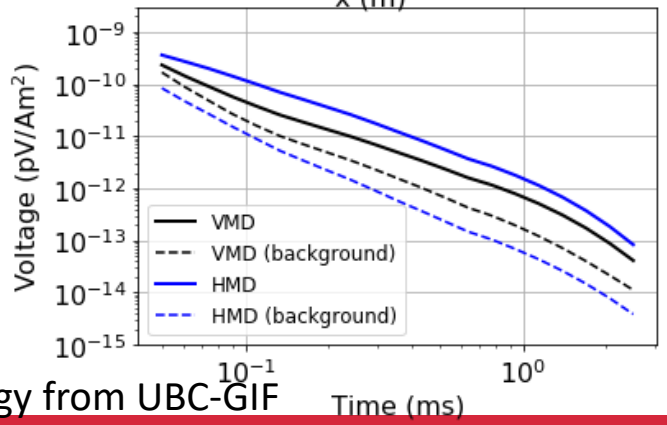


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

VMD vs. HMD: profile line data







HMD is better coupled to the vertical conductor

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF